Status of the FNAL Neutrino Program and Future Prospects

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Fermilab

New Developments of Flavor Physics

Tennomaru, Aichi, Japan

March 9-10, 2009

Outline

- The Current and Near Term Program
- Physics goals of the future program
- NOνA : Capabilities and Status
- The US program beyond NOvA
- Summary and Conclusions

The Current Neutrino Program

- 8 GeV protons from the Booster
  - Neutrinos from Booster Neutrino Beam (BNB)
    - **To MiniBooNE (running)**
    - To SciBooNE (completed in August 2008)

- 120 GeV protons from the Main Injector

  Neutrinos from NuMI
    - **To MINOS (running)**
    - To MINERvA (completing construction 2009, installation 2010)
    - To NOvA (beginning construction 2009)

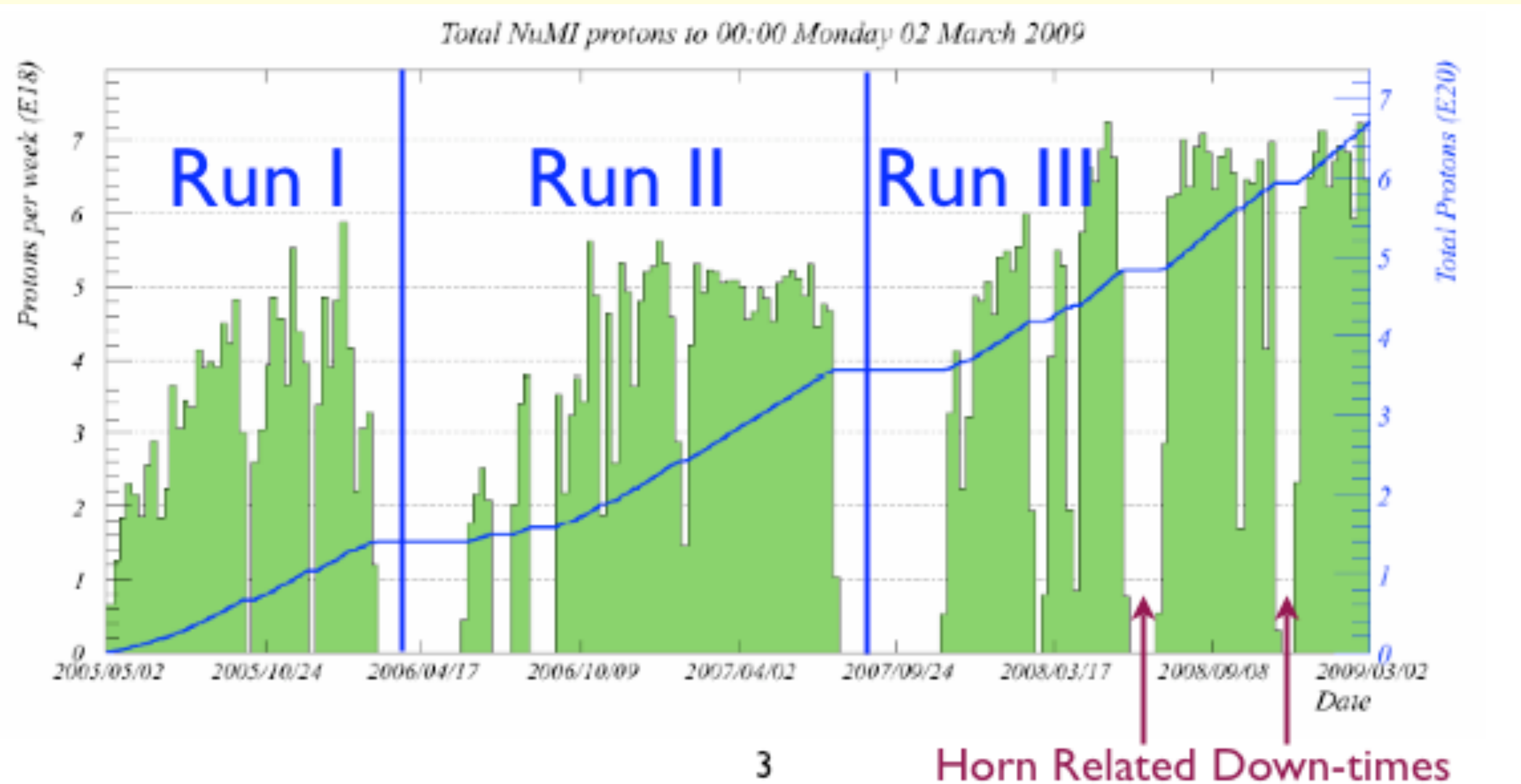
The Current Neutrino Program

- 8 GeV protons from the Booster
  - Neutrinos from Booster Neutrino Beam (BNB)
    - **To MiniBooNE (running)**
    - To MicroBooNE (approved, design phase)

- 120 GeV protons from the Main Injector
  - Neutrinos from NuMI
    - **To MINOS (running)**
    - To ArgoNeuT (liquid argon TPC test) (installation in progress)
    - To MINERvA (completing construction 2009, installation 2010)
    - To NOvA (beginning construction 2009)

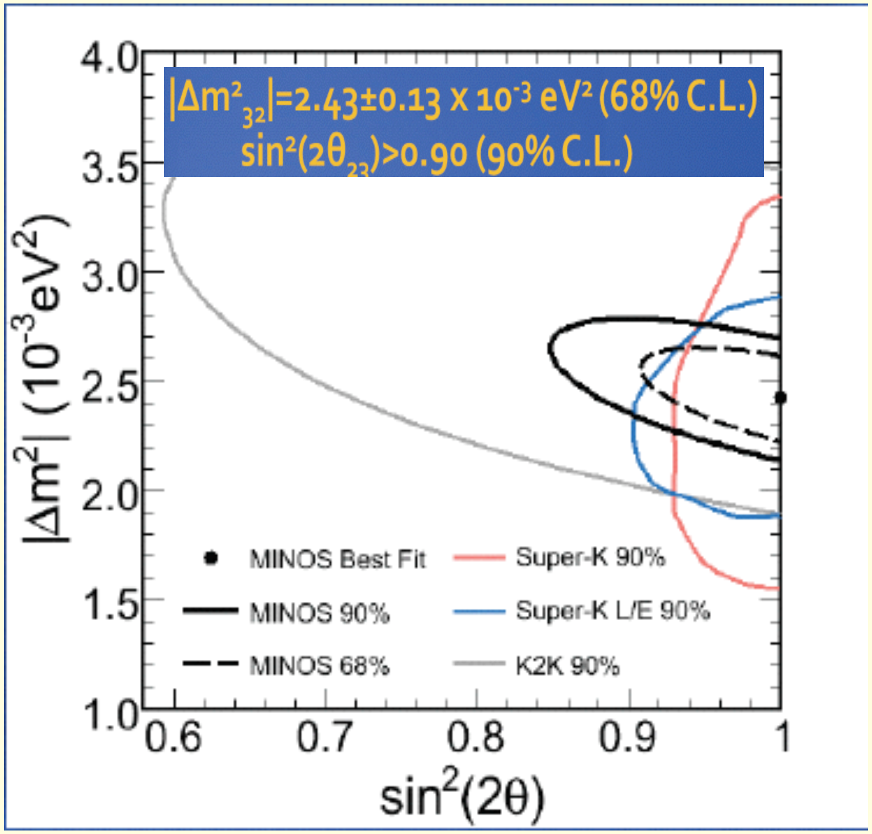
→ Neutrino Oscillations

NuMI Beam Performance

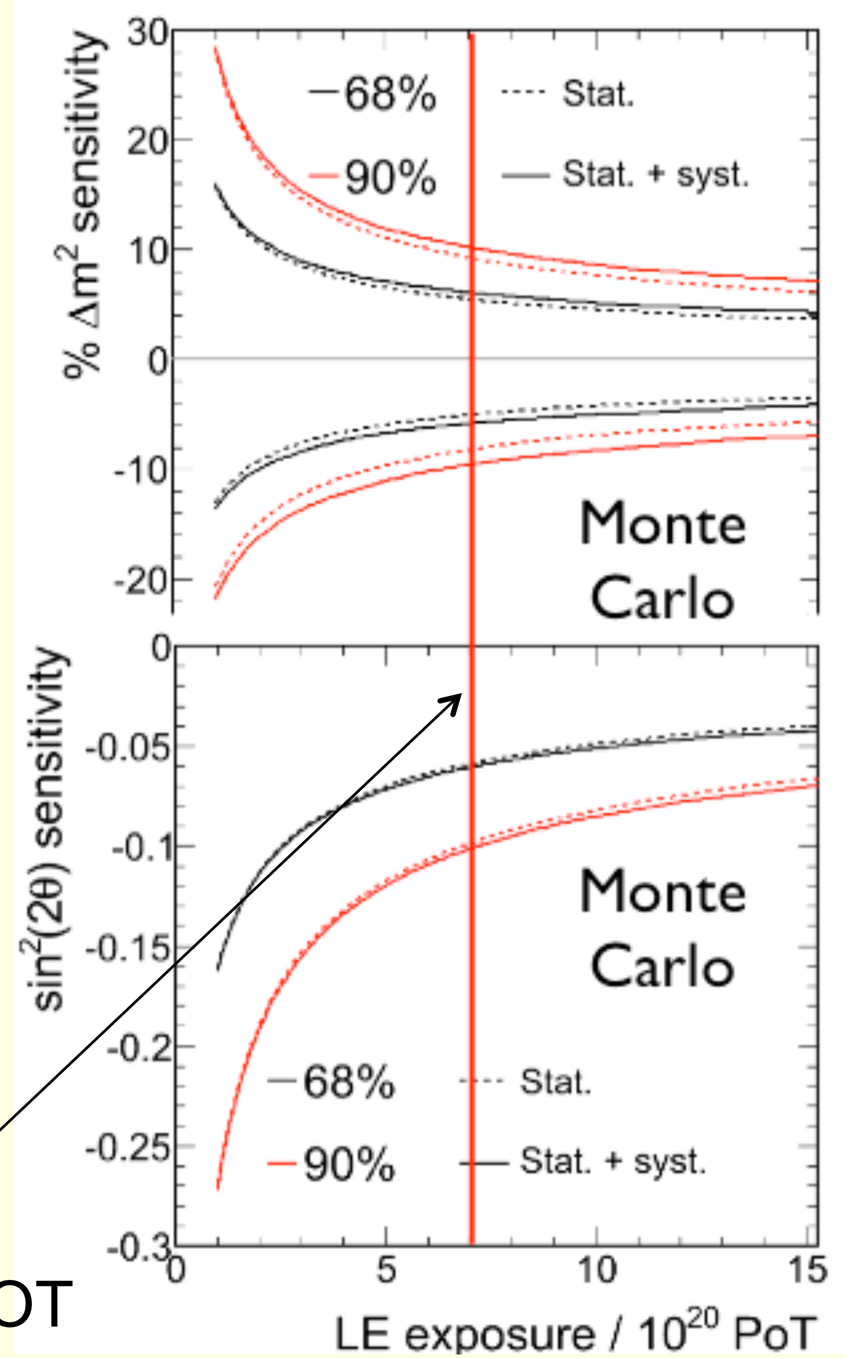


MINOS ν_μ disappearance

3.2×10^{20} POT



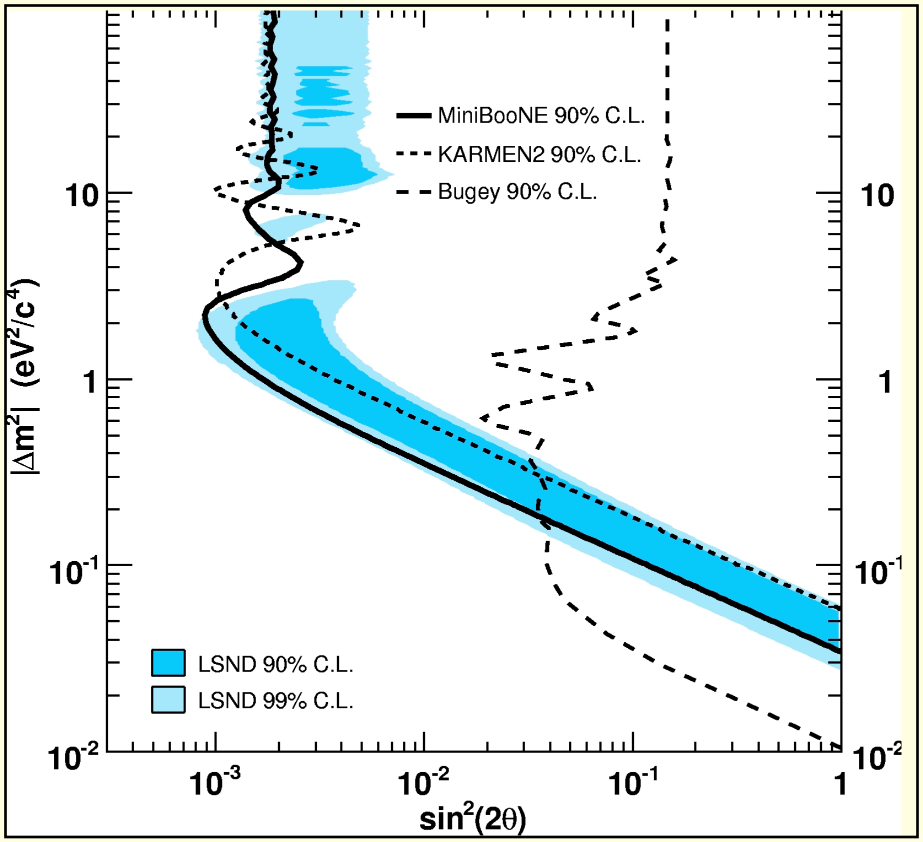
PRL Vol. 101, 131802 (2008)



Next result – 7×10^{20} POT

MiniBooNE $\nu_\mu \rightarrow \nu_e$ appearance

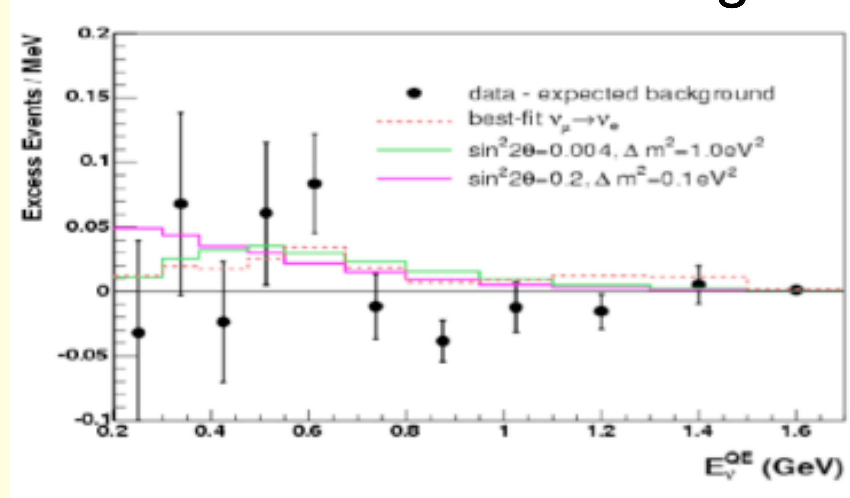
5 x 10 ^{20} POT



Phys. Rev. Lett. 98, 231801 (2007)

Additional data brings total to 6.5x10 ^{20}

Anti-neutrino running



3.4x 10 ^{20} POT

The Quest for θ_{13}

Flavor eigenstate $\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$ Mass eigenstate

At Δ_{atm} we measure the product θ_{13} and θ_{23}

$$P_{vac}(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{atm},$$

$$\Delta_{atm} \approx 1.27\left(\frac{\Delta m^2_{32}L}{E}\right),$$

$$P_{mat}(\nu_\mu \to \nu_e) \approx \left(1 \pm 2\frac{E}{E_R}\right)P_{vac}(\nu_\mu \to \nu_e)$$

$$E_R = \frac{\Delta m^2_{32}}{2\sqrt{2}G_F N_e} = 12\ \text{GeV}\left(\frac{\Delta m^2_{32}}{2.5\times 10^{-3}\ \text{eV}^2}\right)\left(\frac{1.4\ \text{g cm}^{-3}}{Y_e\rho}\right)$$

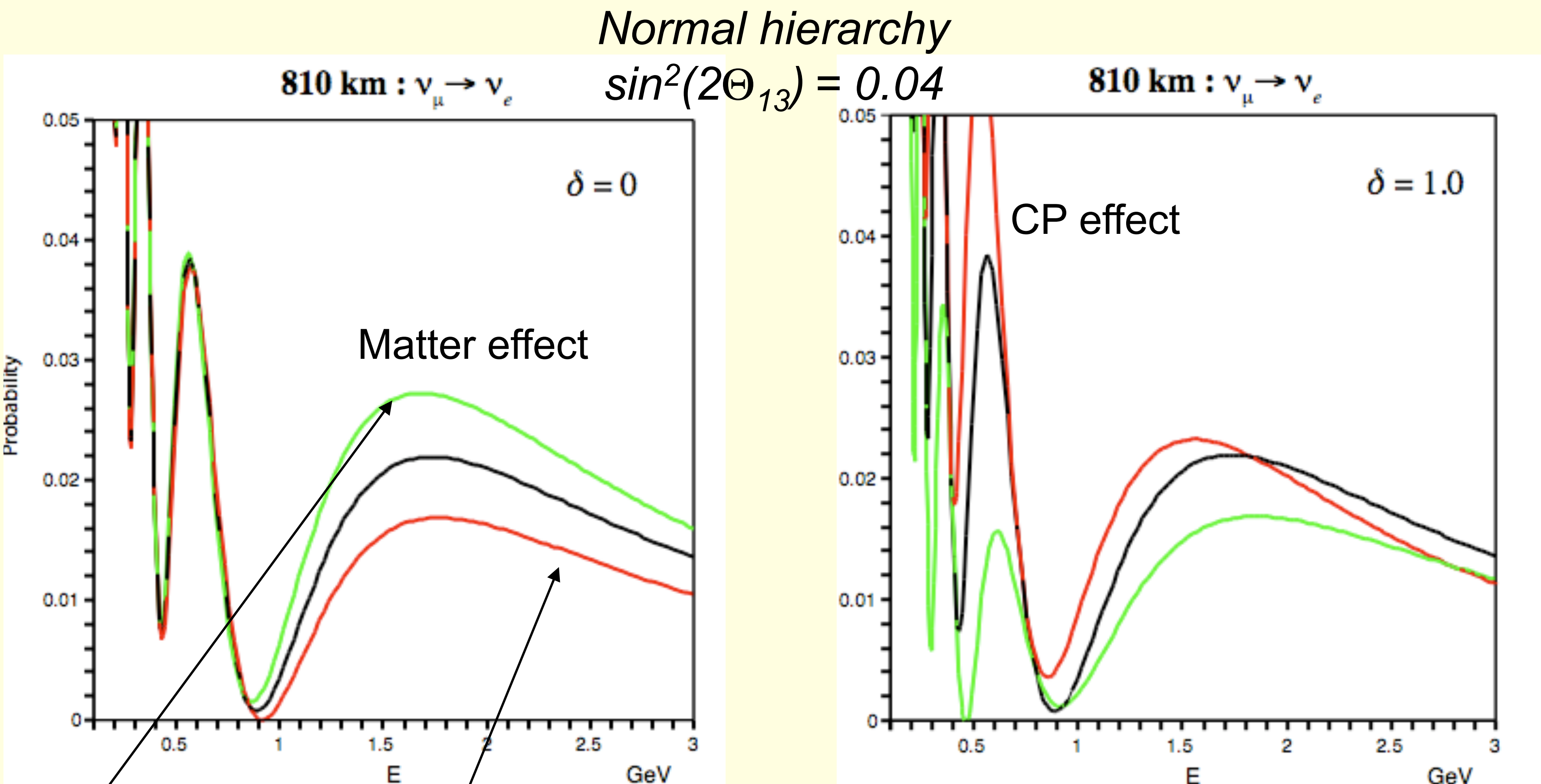
ν oscillations are enhanced, $\bar{\nu}$ are suppressed (or vice versa depending on the mass hierarchy)

$$\Delta P_\delta(\nu_\mu \to \nu_e) \approx J_r \sin\Delta_{sol}\sin\Delta_{atm}(\cos\delta\cos\Delta_{atm} -+ \sin\delta\sin\Delta_{atm}),$$

$$J_r = \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13},$$

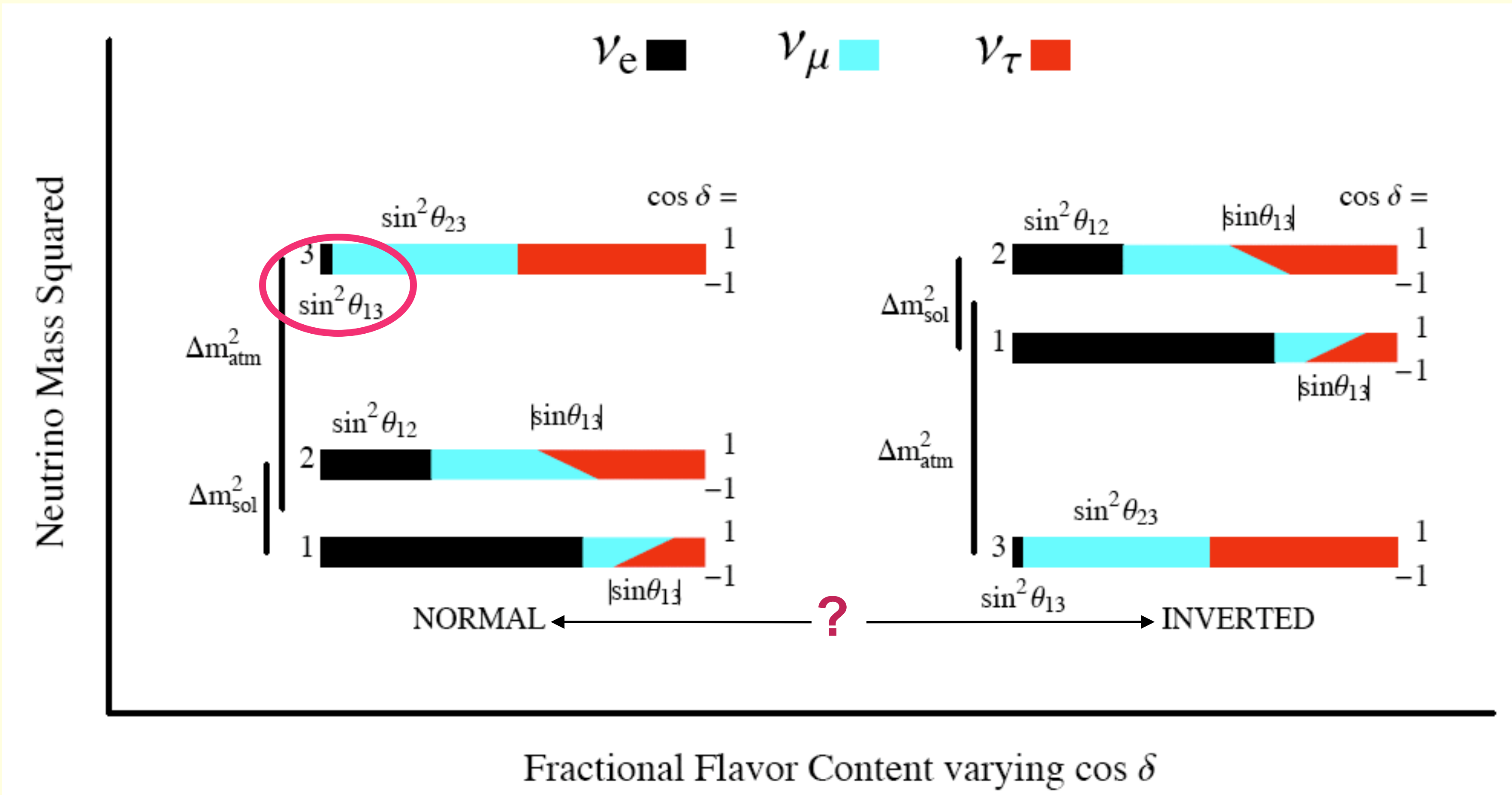
And the CP phase

Matter Effects and CP

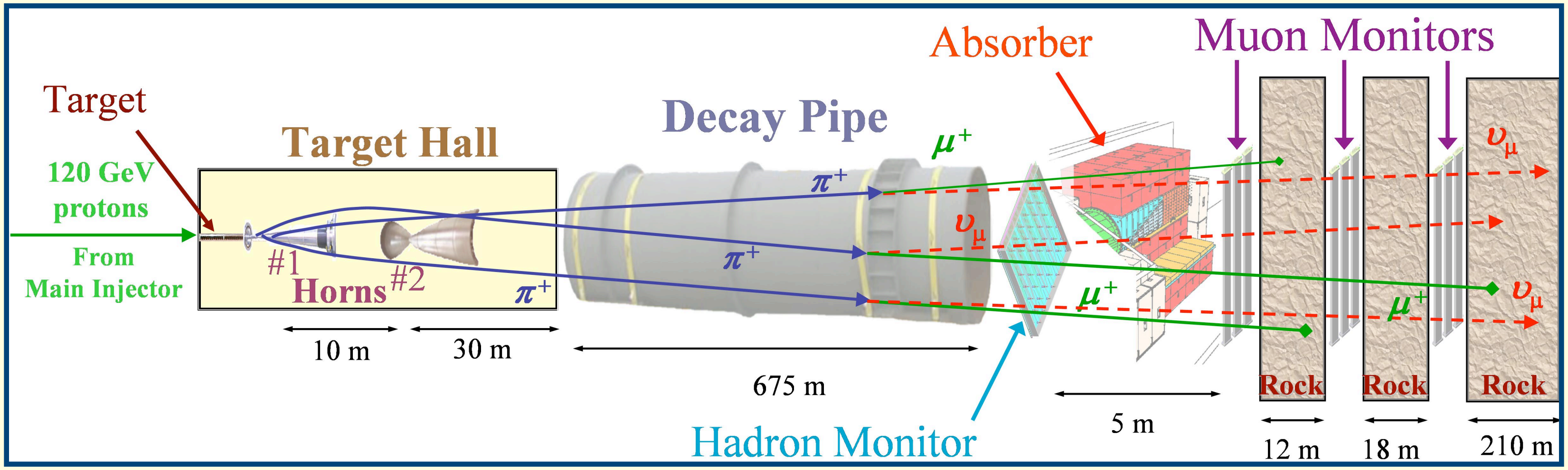


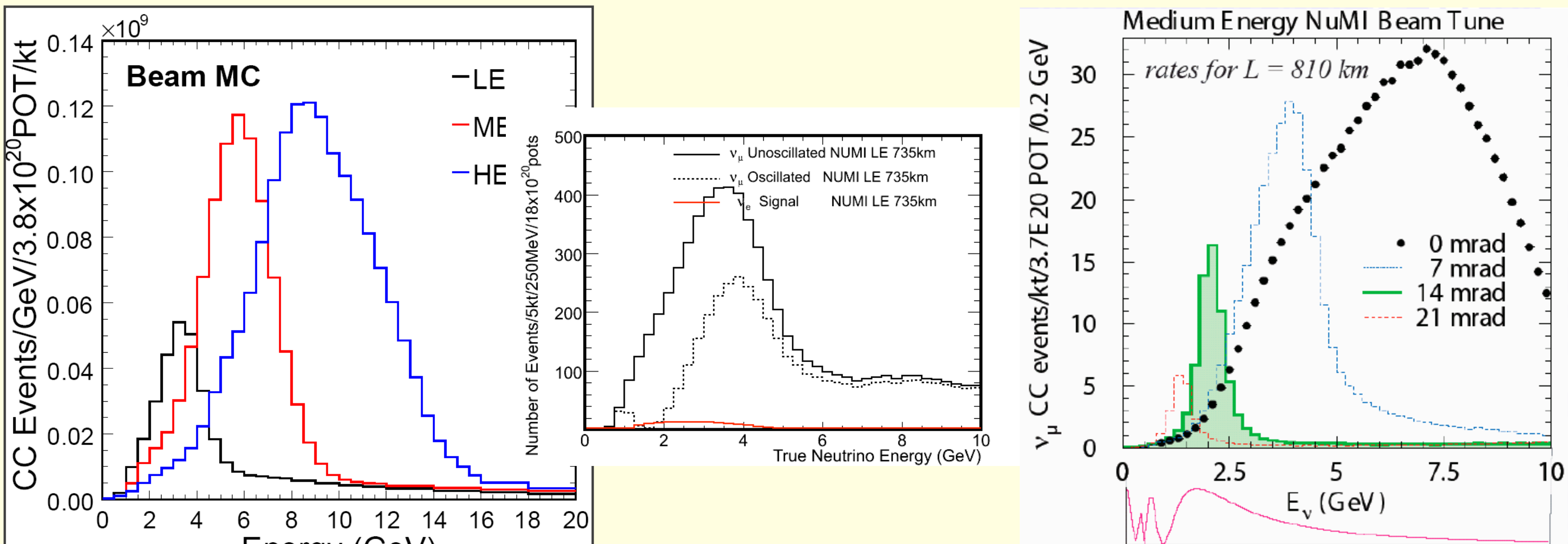
ν's and and anti-ν's can be used to distinguish ambiguities

θ_{13} ,mass hierarchy and δ_{CP}



The NuMI Beam

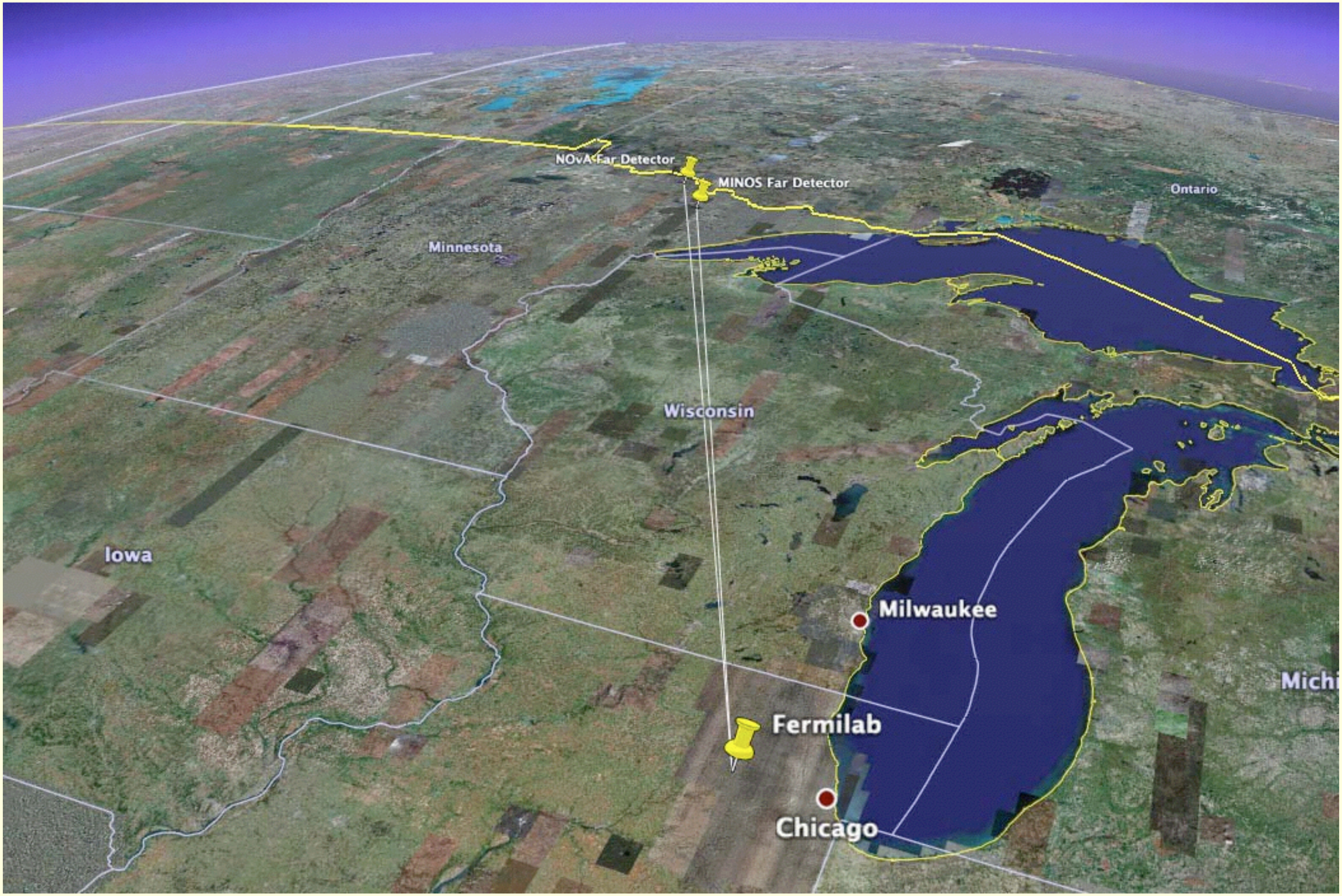




Target - horn separation sets the neutrino energy spectrum.

Off-axis detector location sees a narrow band beam

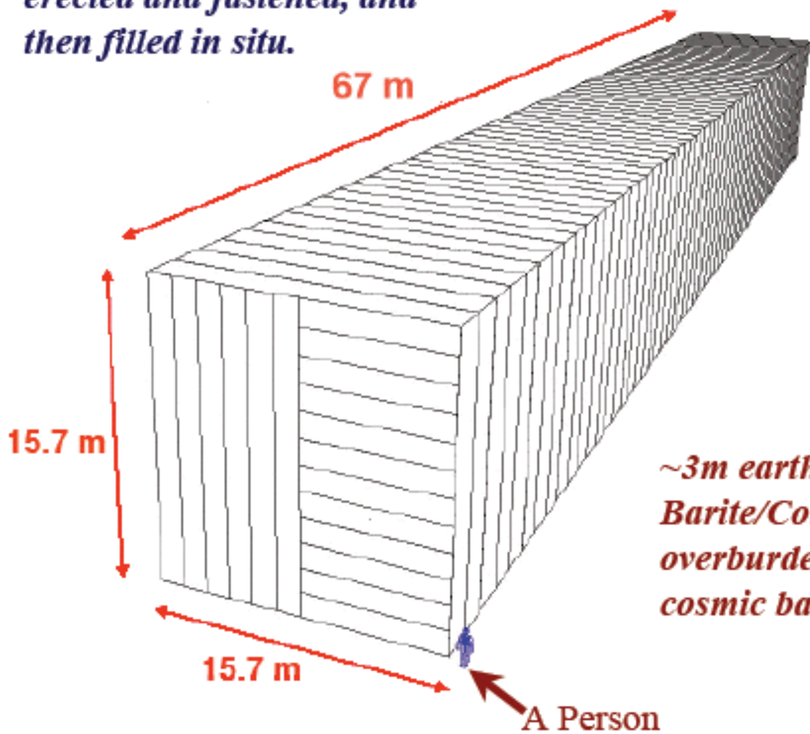
NOνA : NuMI Off-Axis



NOνA

Far Detector

Construction:
Empty planes will be erected and fastened, and then filled in situ.

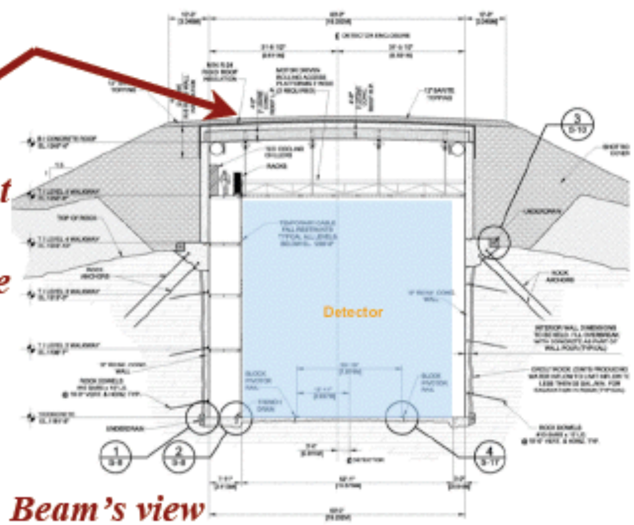


15kT Total Mass
(70% Scintillator)

1003 planes of detector supported in blocks of 31

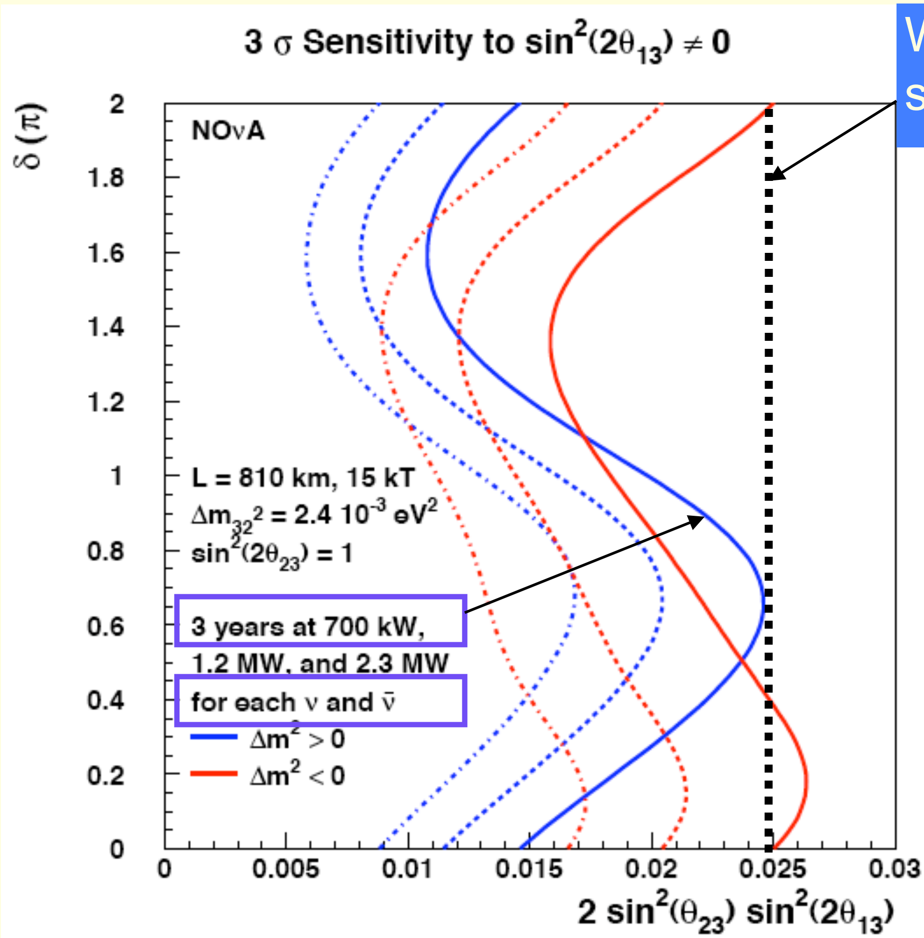
385000+ cells

~3m earth equivalent Barite/Concrete overburden to reduce cosmic backgrounds



Beam's view

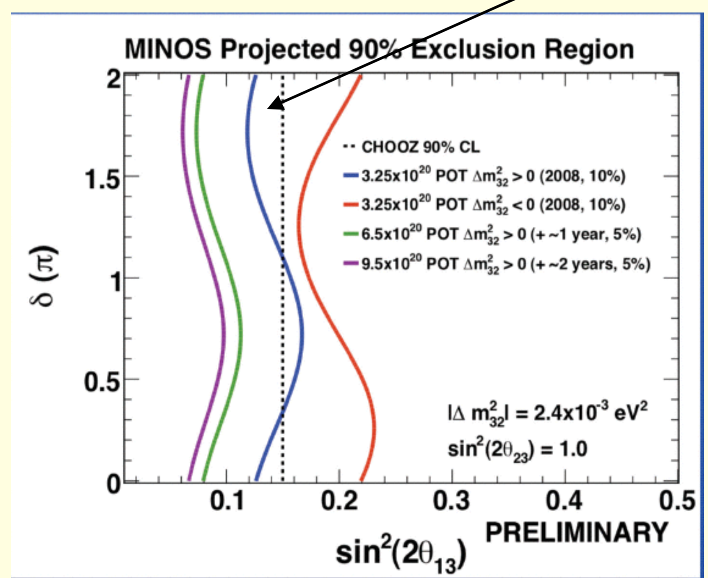
NOνA Sensitivity



We have a ~3σ discovery potential for $\sin^2 2\theta_{13} \geq 0.025$ for ALL values of δ_{CP}.

Expectation for MINOS

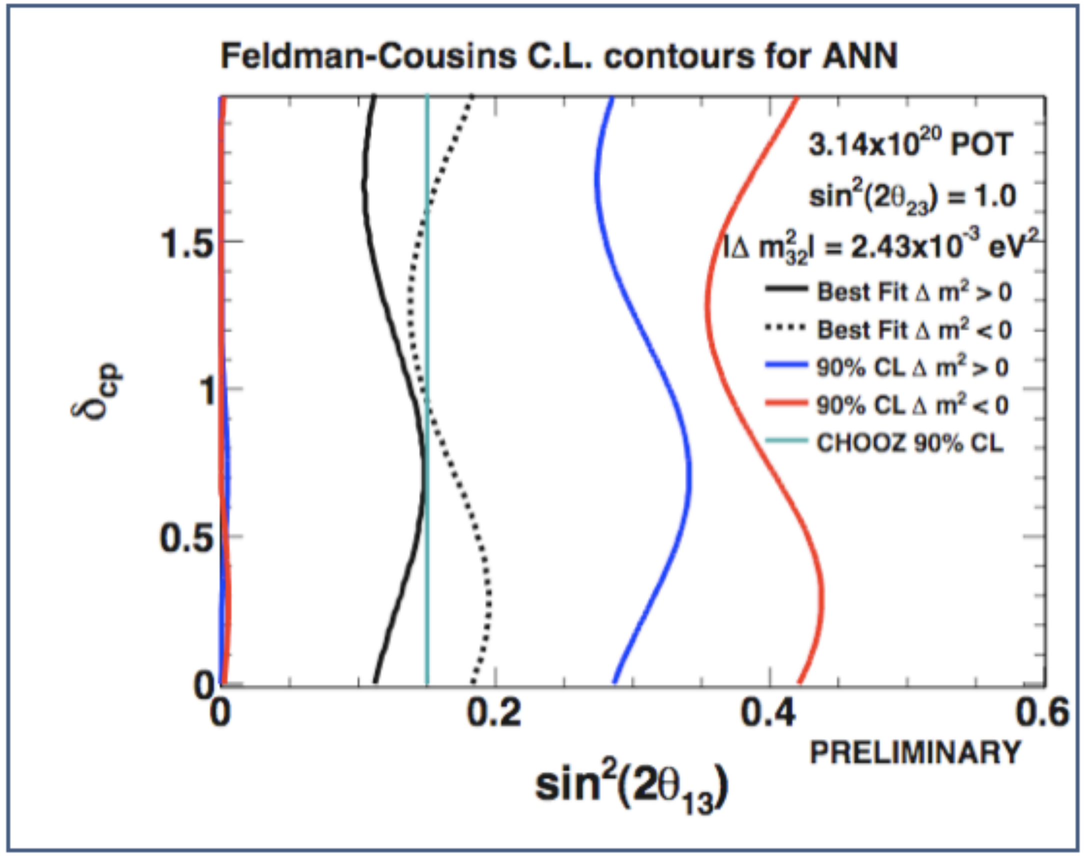
More than an order of magnitude improvement over the current 90% CL



MINOS 90% CL in $\sin^2 2\theta_{13}$

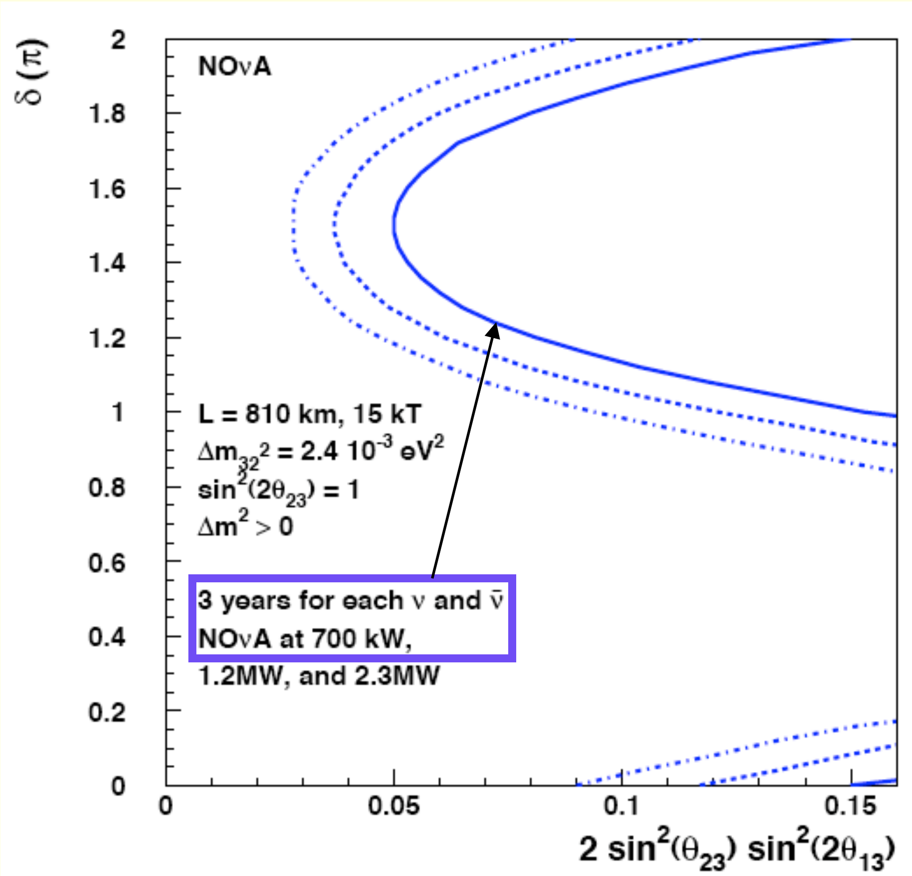
Fitting the oscillation hypothesis to our data

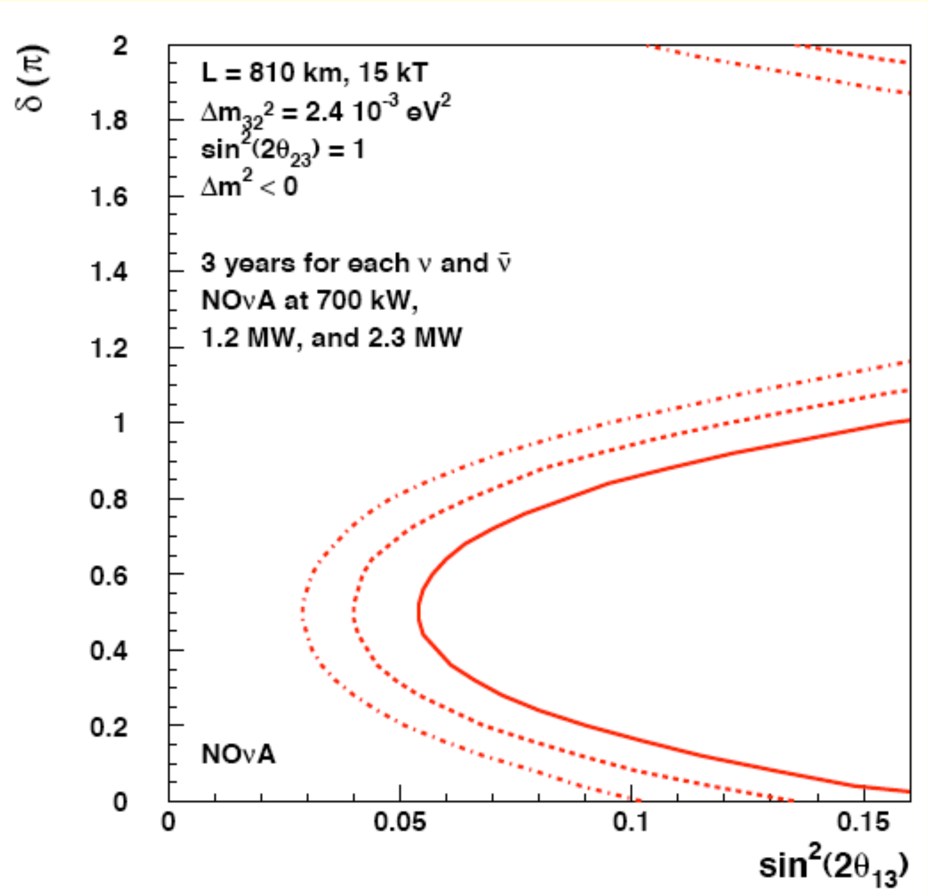
- Plot shows 90% limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
  - shown at the MINOS best fit value for Δm^2_{32} and $\sin^2 2\theta_{23}$.
  - for both mass hierarchies
- A Feldman-Cousins method was used.
- Results are for primary selection and primary separation method.



M. Sanchez - February 27,2009 Seminar at FNAL

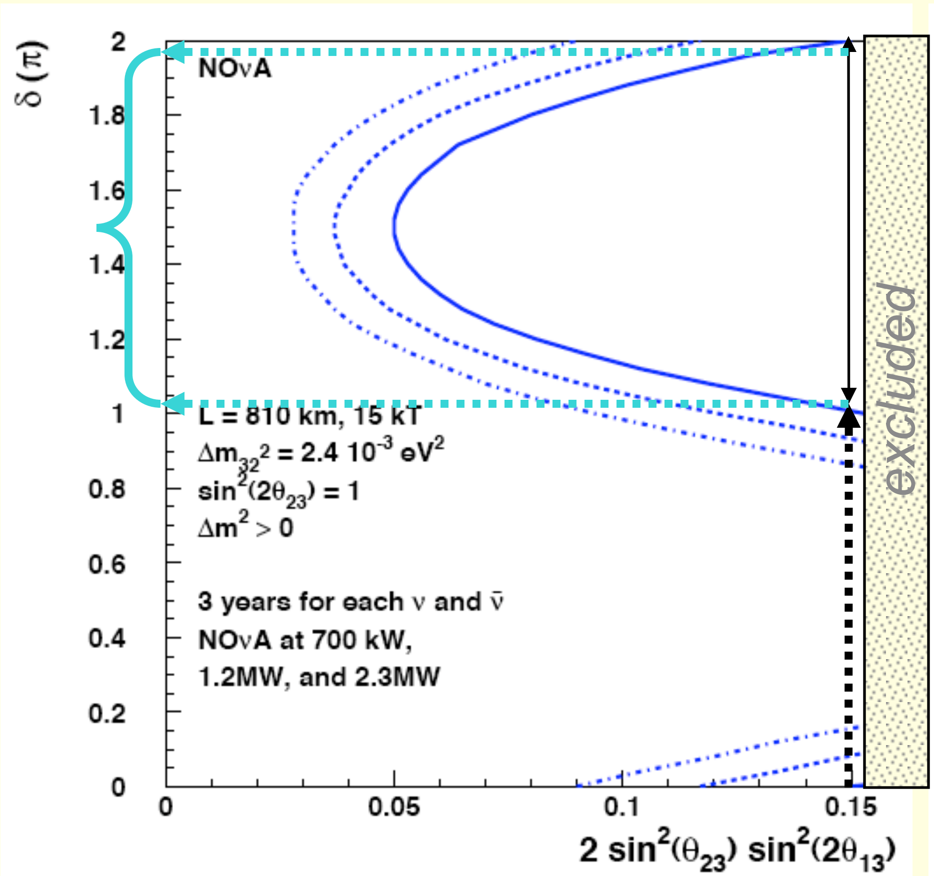
NOνA Sensitivity to the Mass Hierarchy

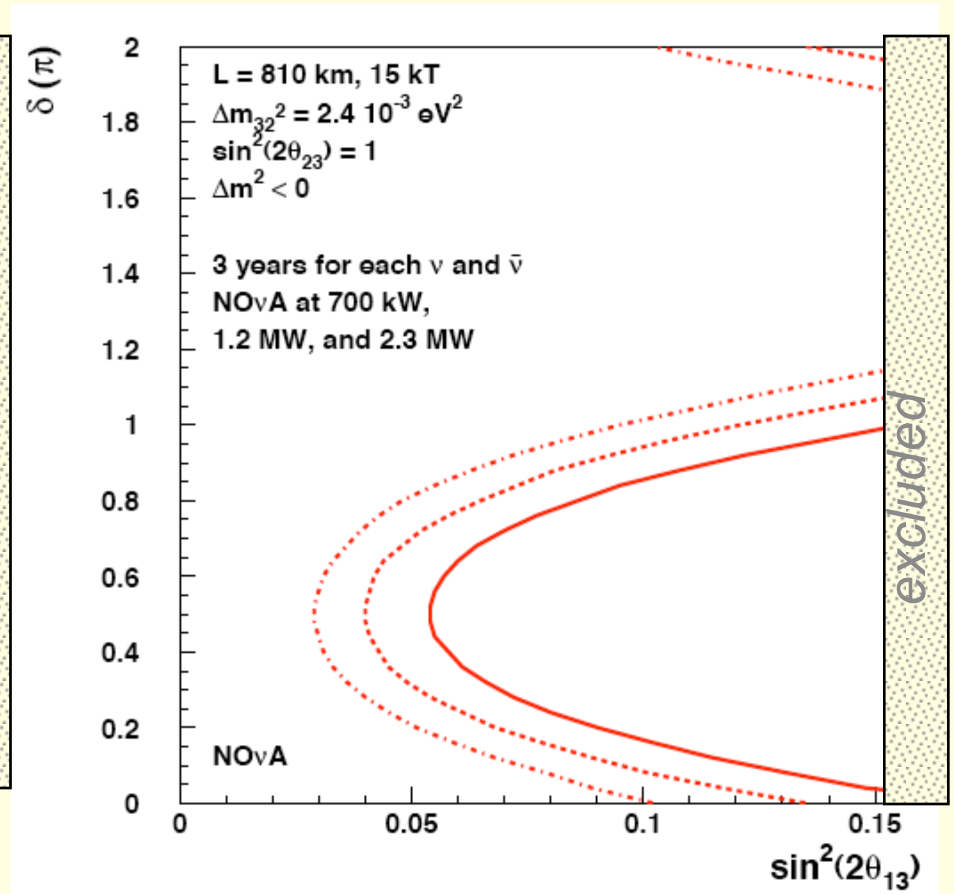




Interpreting
NOνA Sensitivity to the Mass Hierarchy

95% CL

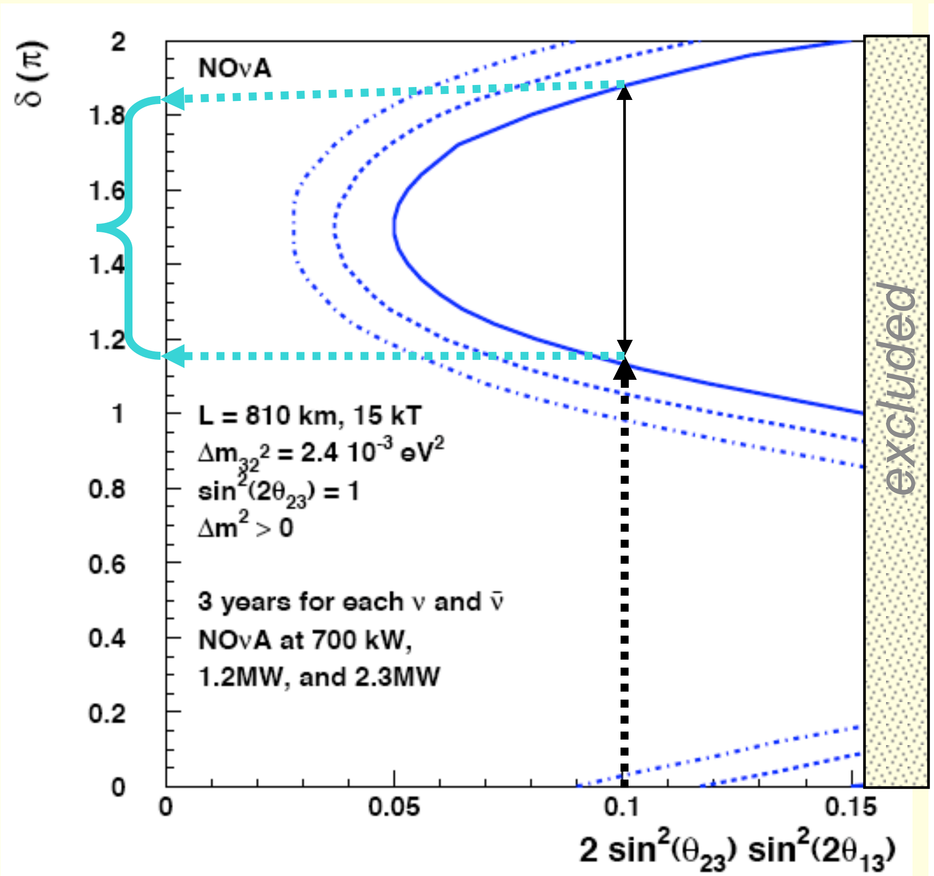


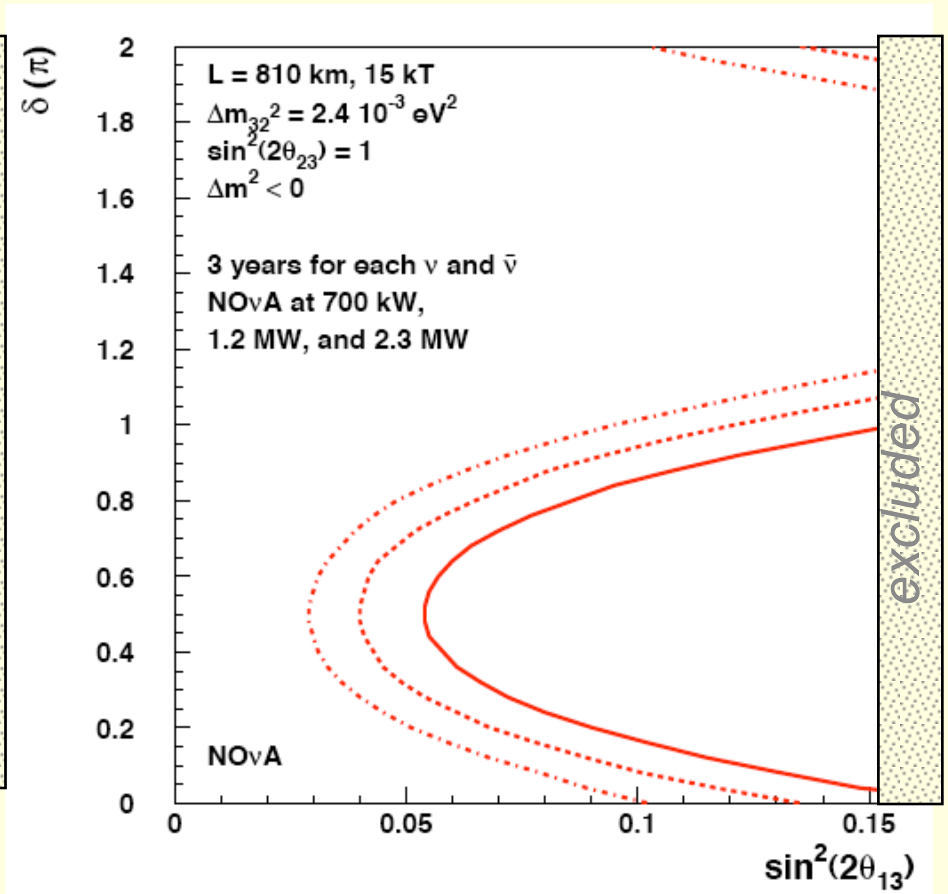


If $\sin^2 2\theta_{13} = 0.15$, for 50% of the possible values of δ_{CP} the mass hierarchy can be determined at 95%CL

Interpreting
NOνA Sensitivity to the Mass Hierarchy

95% CL

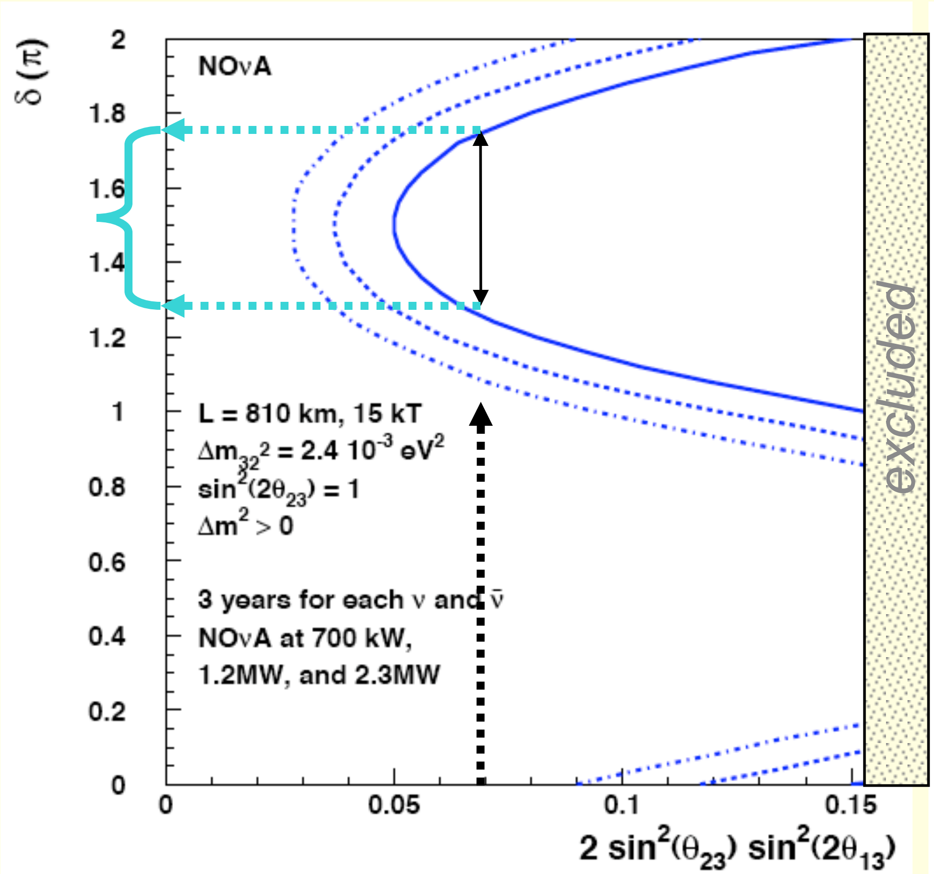


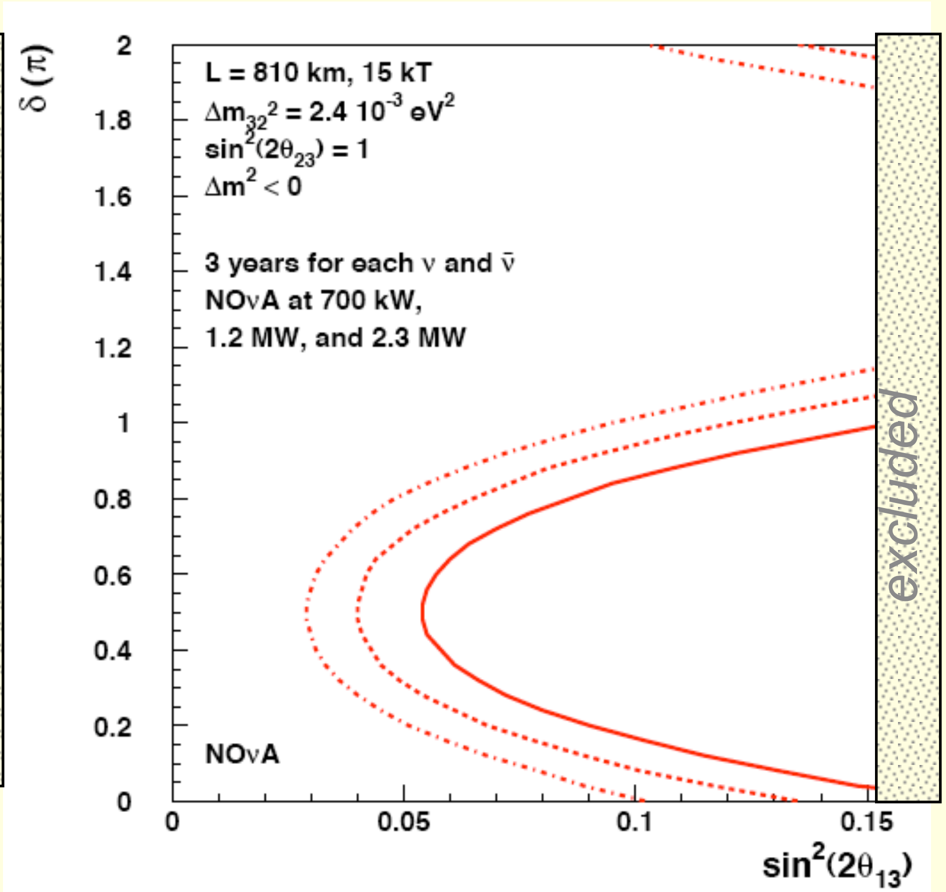


If $\sin^2 2\theta_{13} = 0.10$, for 36% of the possible values of δ_{CP} the mass hierarchy can be determined at 95%CL

Interpreting
NOνA Sensitivity to the Mass Hierarchy

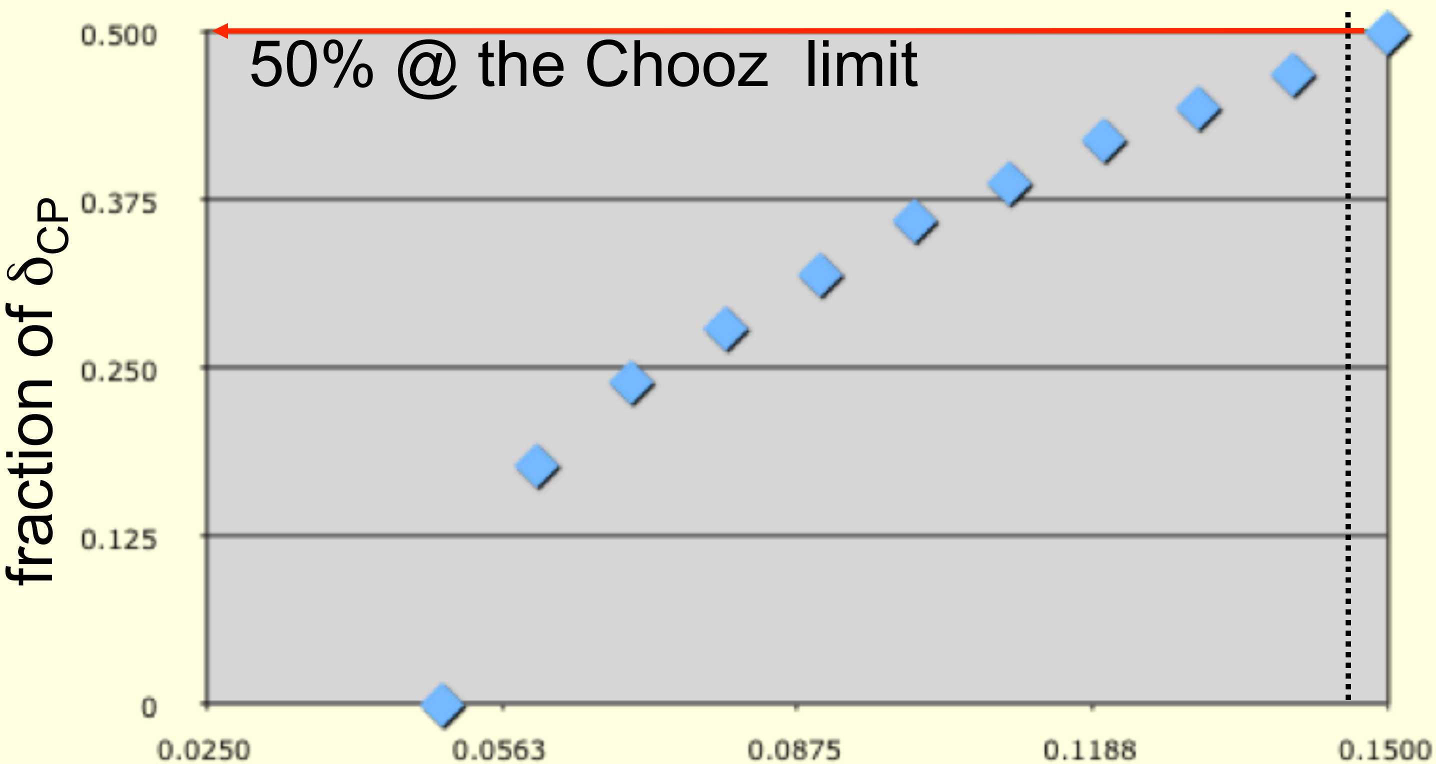
95% CL





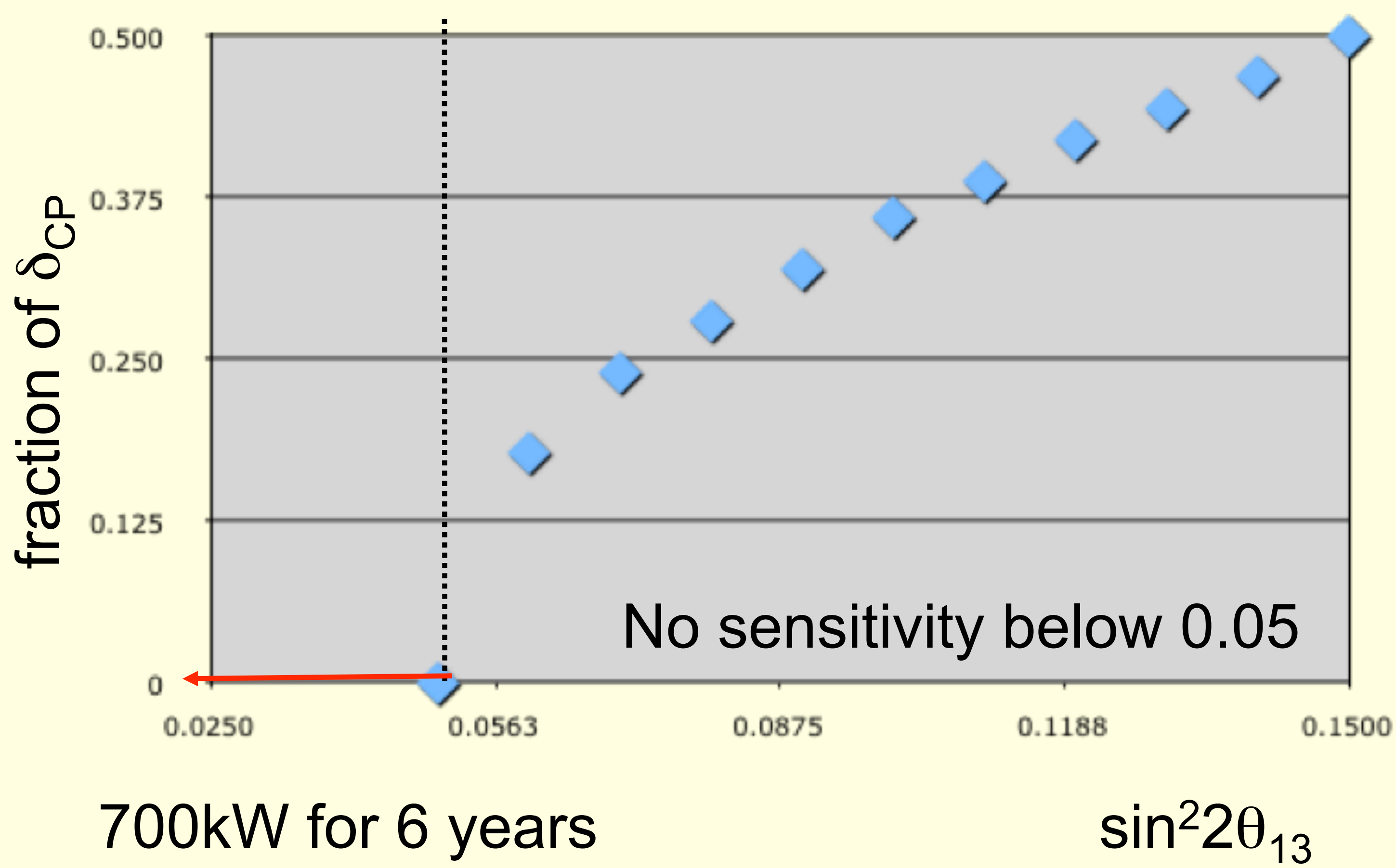
If $\sin^2 2\theta_{13} = 0.07$, for 24% of the possible values of δ_{CP} the mass hierarchy can be determined at 95%CL

NOνA 95% CL sensitivity to the Mass Hierarchy

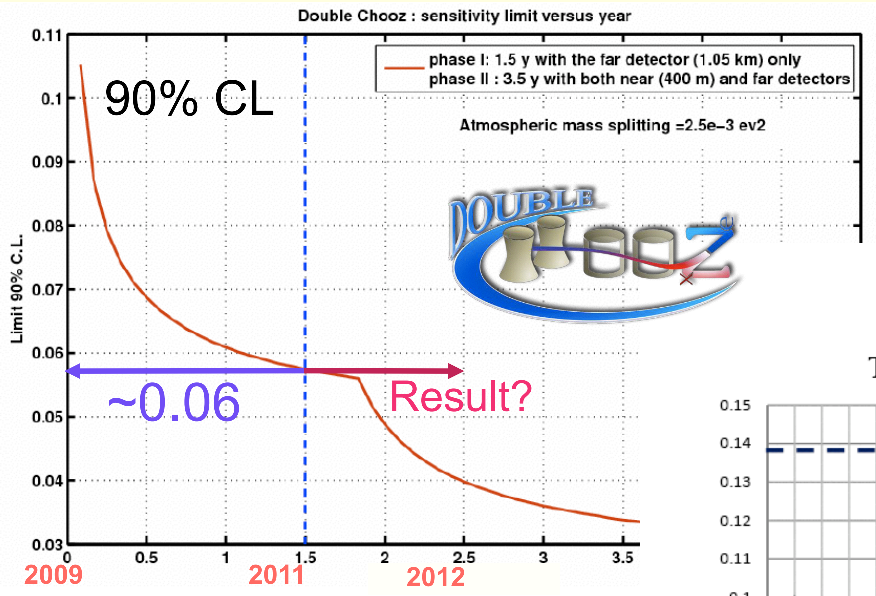


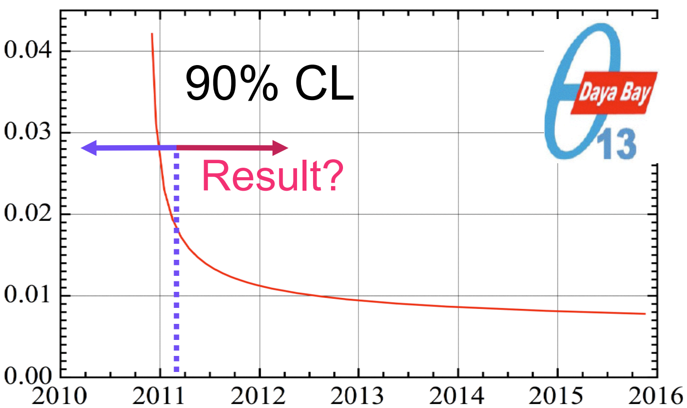
700kW for 6 years $\sin^2 2\theta_{13}$

NOνA 95% CL sensitivity to the Mass Hierarchy

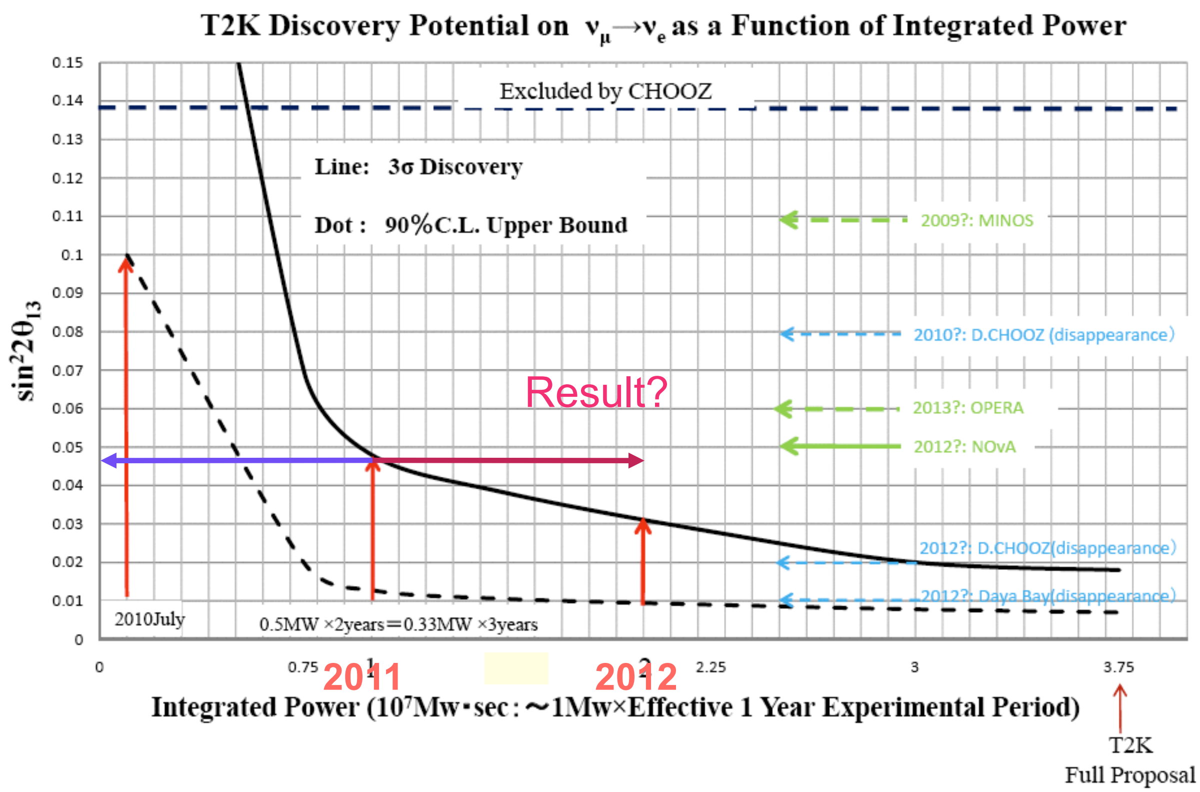


What are the prospects for knowing $\sin^2 2\theta_{13}$?

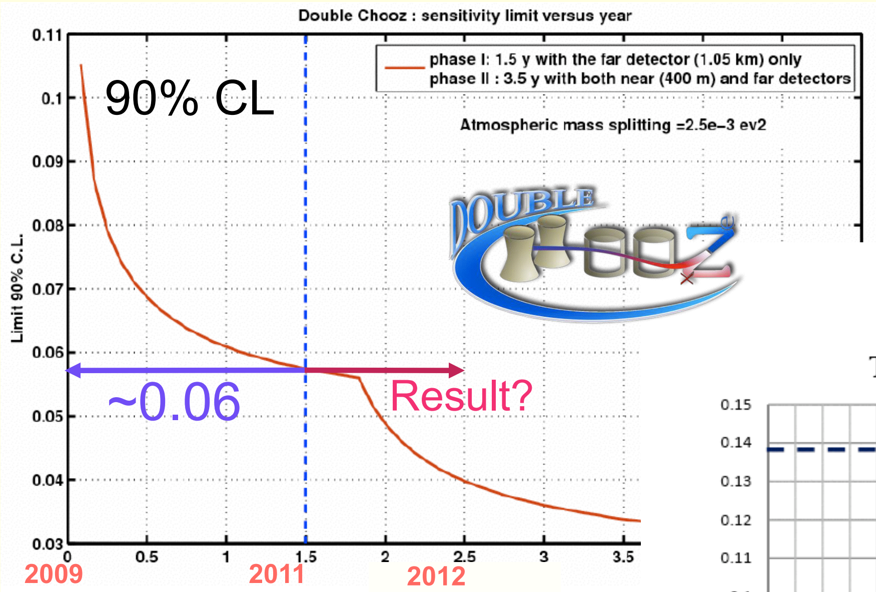


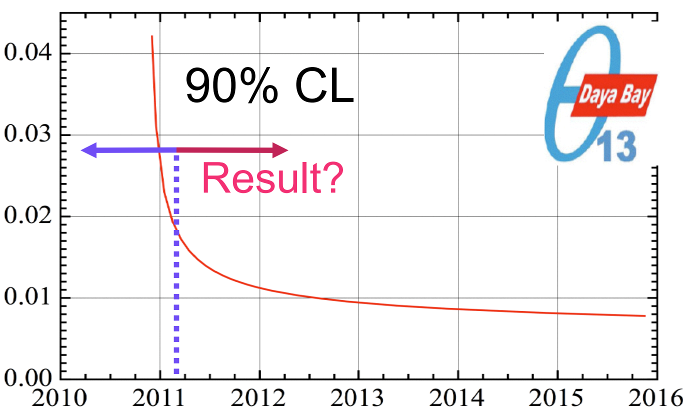


Takuya Hasegawa - NNN08



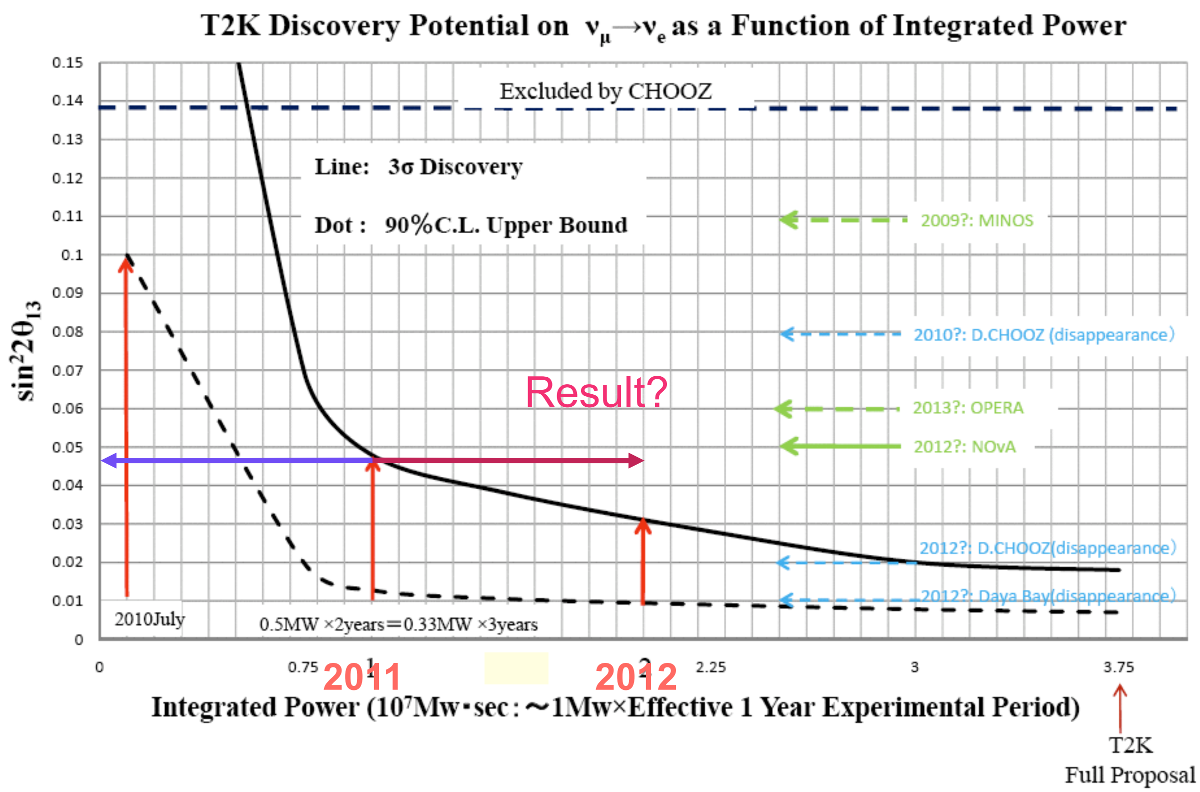
What are the prospects for knowing $\sin^2 2\theta_{13}$?



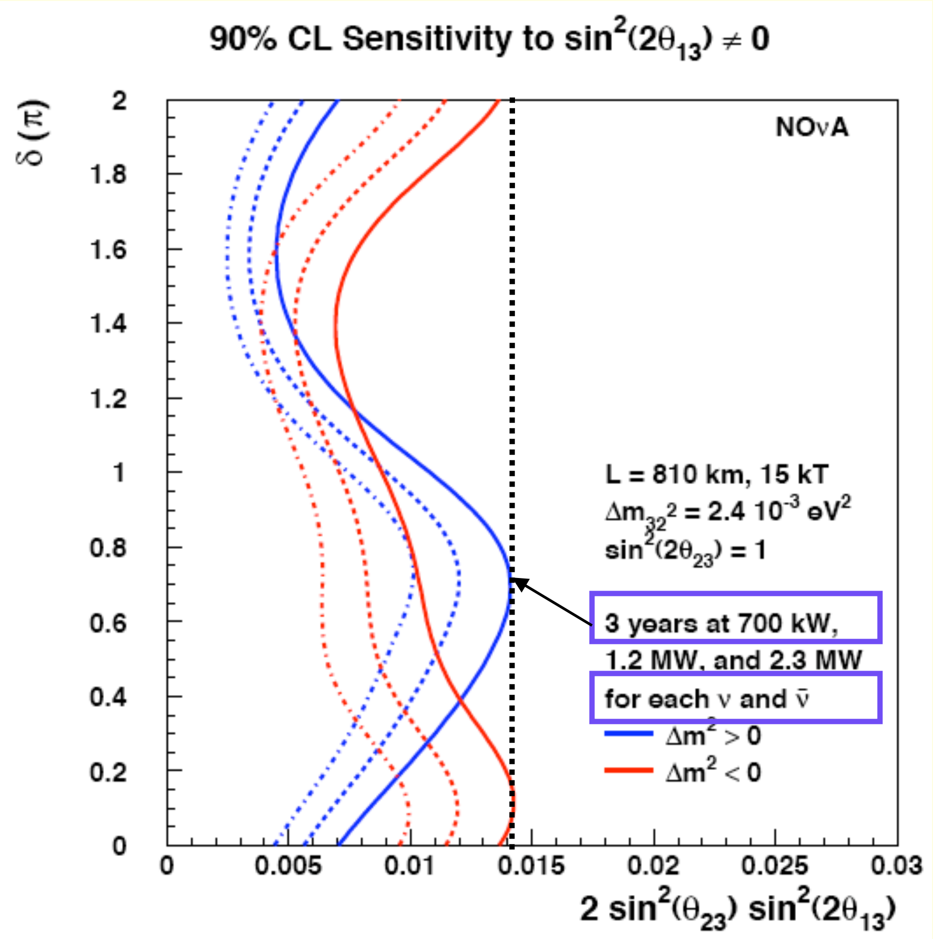


By 2012, we should have
a good indication if $\sin^2 2\theta_{13} > 0.05$

Takuya Hasegawa - NNN08



NOνA Sensitivity for small $\sin^2 2\theta_{13}$



We can reach a 90% CL limit for $\sin^2 2\theta_{13} < 0.015$ for ALL values of δ_{CP}.

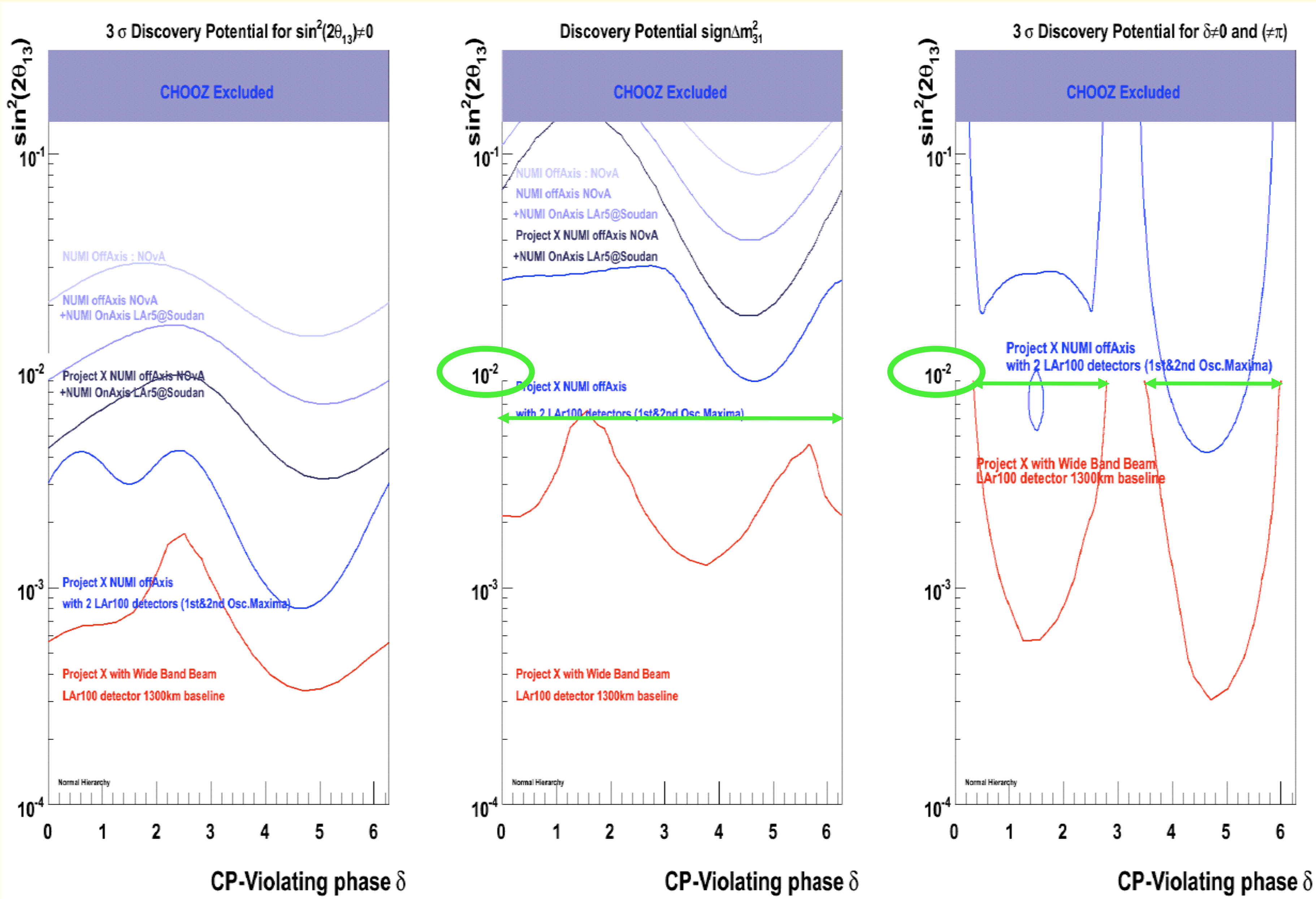
Neutrino Program Evolution beyond the "Phase I" θ_{13} experiments

- Numerous studies over the past several years have laid out options for further exploring the neutrino sector
  - In particular, searching for CP violation
- i.e. BNL-FNAL US long baseline neutrino experiment study (March 2006-June 2007) explored
  - Beam options
    - NuMI , <u>new</u> Wide Band Beam at a longer baseline
    - On and off axis detector locations
  - Detector technology options
    - Water cerenkov, liquid argon
- These studies make sense in the context of a non-zero determination of θ_{13}

General Conclusions

- Future experiments using conventional* neutrino beams can be designed to have 3-5σ discovery potential for measuring **CP violation and the neutrino mass hierarchy** for values of $\sin^2 2\theta_{13}$ as low as ~ 0.01
- These sensitivities are reached assuming :
  - a **proton source** at the Megawatt level (or decades of running time)
  - a **neutrino beam** optimized to the oscillation probability (covering the 1st and 2nd oscillation maximum)
  - an **experiment baseline > 1000 km** (to improve the sensitivity to determine the mass hierarchy)
  - a **Detector** with effective mass (mass*efficiency) **> 100kT**

- *If nature has made θ_{13} very small we may need to consider a non-conventional neutrino source, i.e. **neutrino factory**



Plot by N. Saoulidou for Fermilab Steering Group

US Particle Physics: Scientific Opportunities

A Strategic Plan
for the Next Ten Years

Report of the Particle
Physics Project
Prioritization Panel

29 May 2008

from P5 report

The Intensity Frontier

The accelerator-based neutrino program

- Measurements of the mass and other properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for understanding the evolution of the universe. The US can build on the unique capabilities and infrastructure at Fermilab, together with the proposed DUSEL, the Deep Underground Science and Engineering Laboratory proposed for the Homestake Mine, to develop a world-leading program in neutrino science. Such a program will require a multi-megawatt proton source at Fermilab.

- The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab.

from P5 report

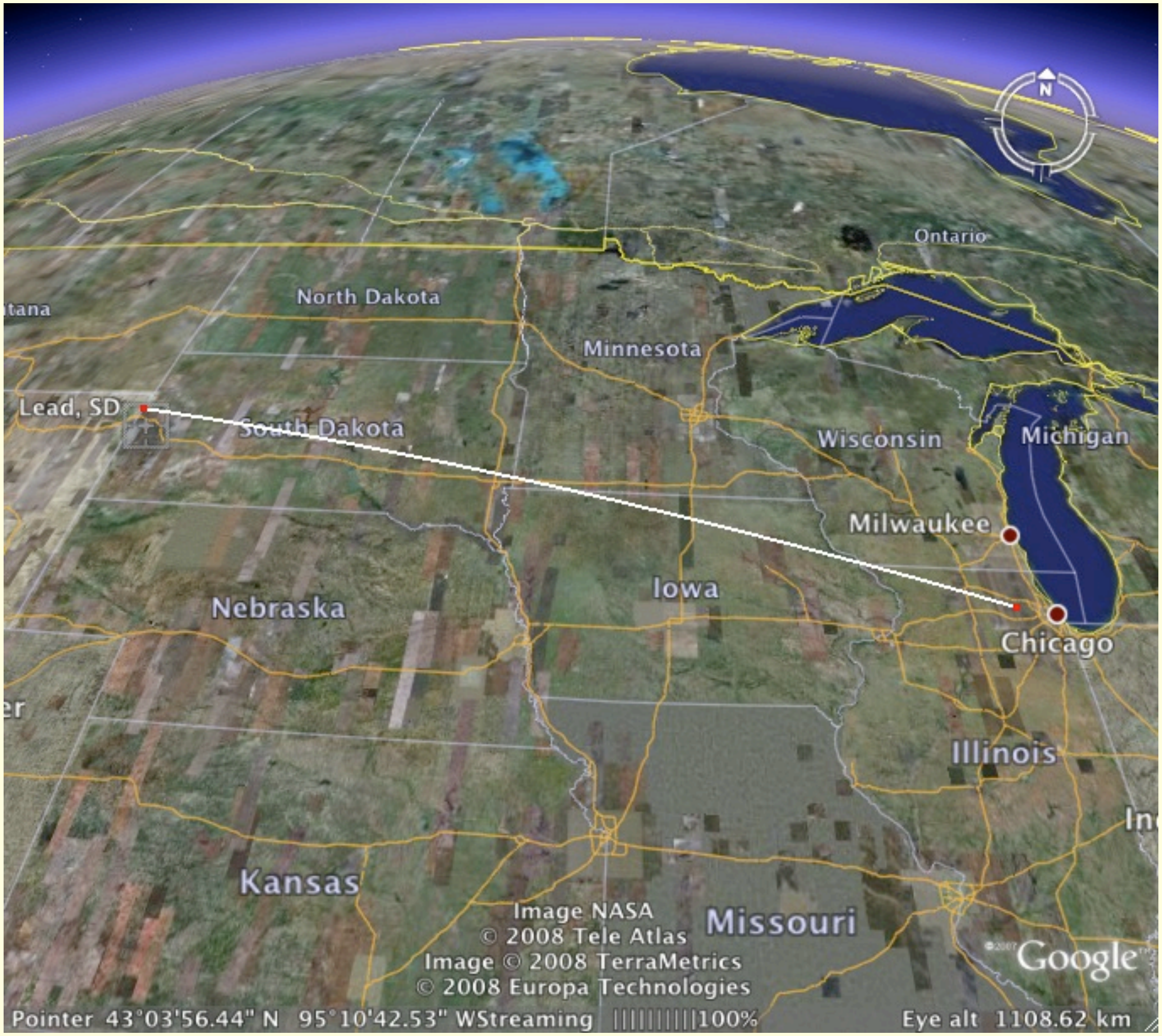
Neutrino Program (cont)

- The panel recommends proceeding now with an R&D program to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D on the technology for a large detector at DUSEL.

- Construction of these facilities could start within the period considered by this report.

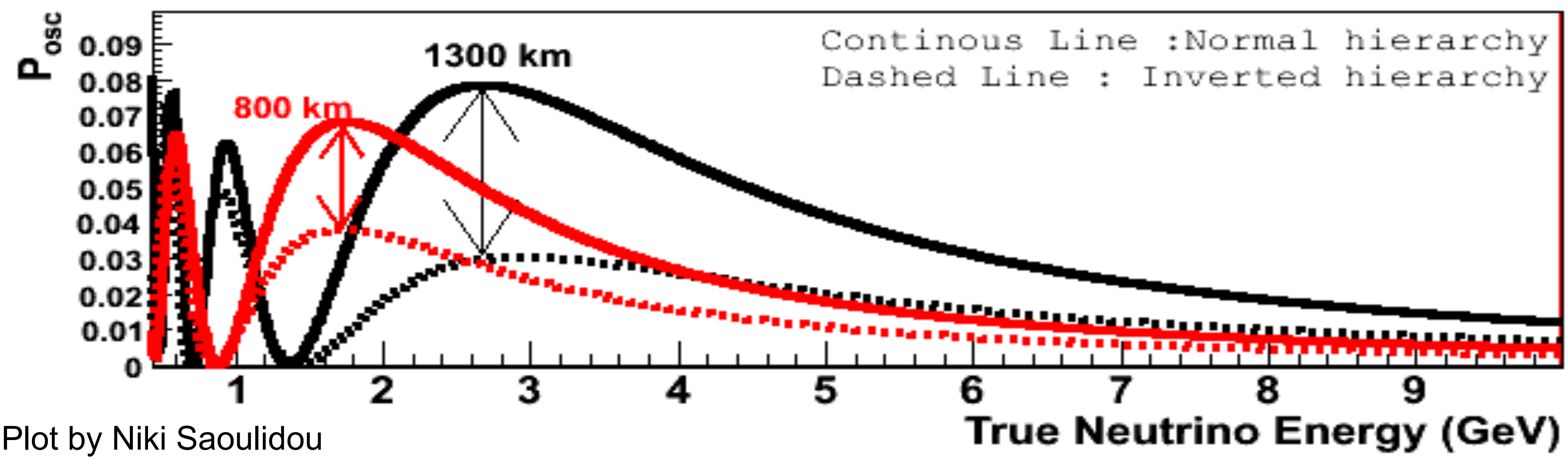
- A neutrino program with a multi-megawatt proton source would be a stepping stone toward a future neutrino source, such as a neutrino factory based on a muon storage ring, if the science eventually requires a more powerful neutrino source. This in turn could position the US program to develop a muon collider as a long-term means to return to the energy frontier in the US

Fermilab to Homestake DUSEL (1290km)



What happens at the longer baseline?

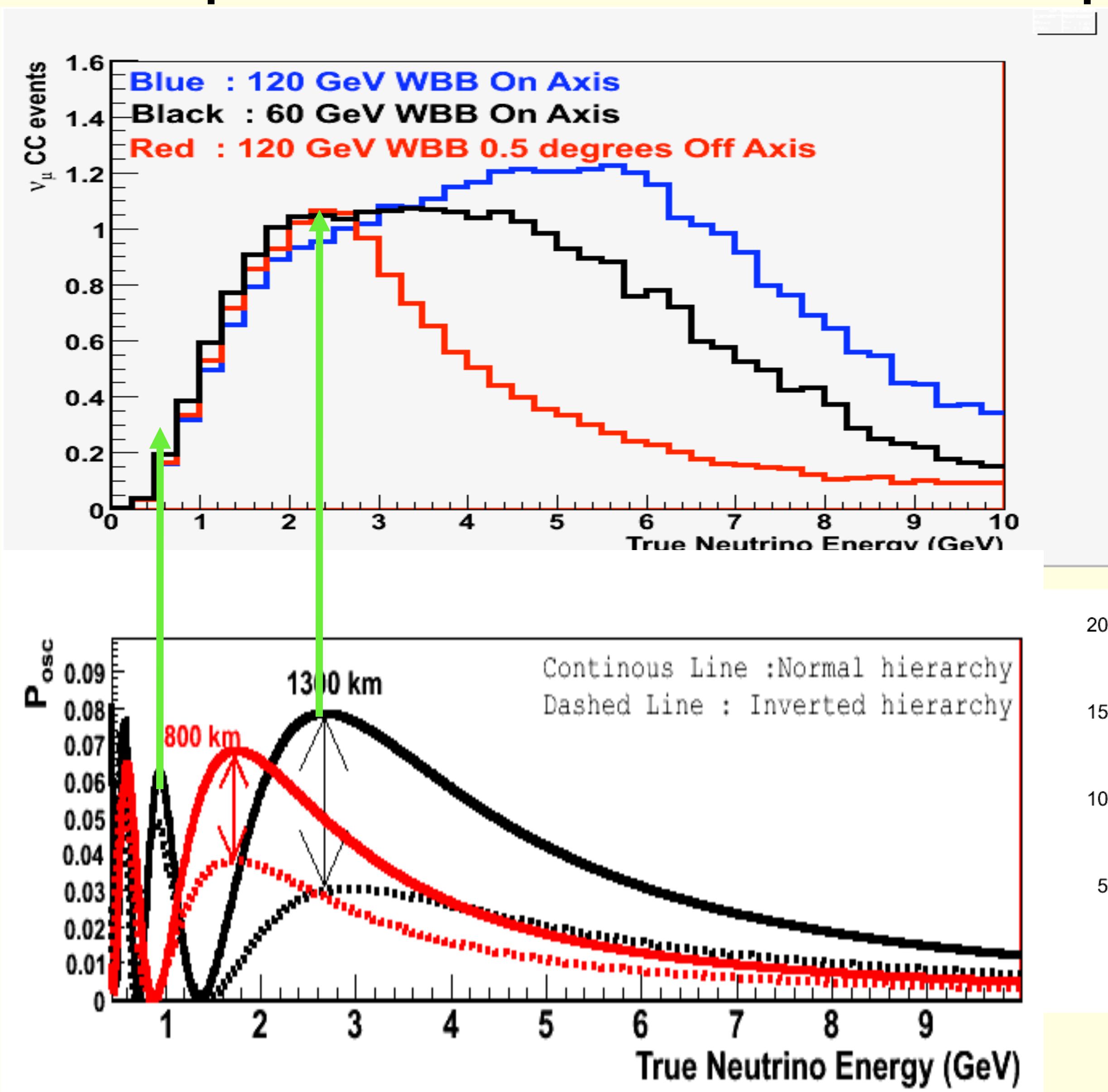
$P(\nu_\mu \rightarrow \nu_e)$

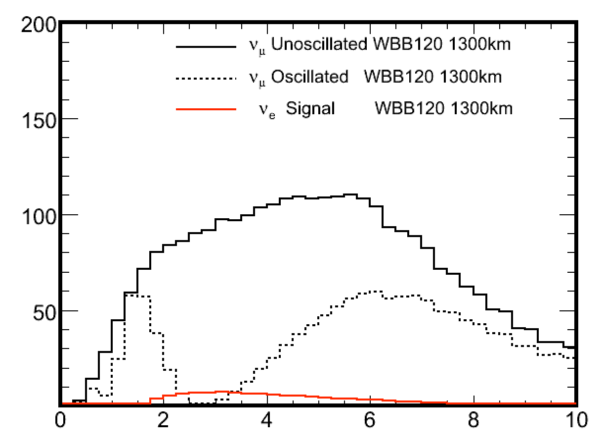


Plot by Niki Saoulidou

- Oscillation maxima are moved to higher energy
- Matter effects are significantly larger

The Experimental Technique : optimize the spectrum to the oscillation probability





		Neutrino Rates				Anti Neutrino Rates			
Beam (mass ordering)	$\sin^2 2\theta_{13}$	δ_{CP} deg.							
		0°	-90°	180°	+90°	0°	-90°	180°	+90°
NuMI LE 12 km offaxs (+)	0.02	76	108	69	36	20	7.7	17	30
NuMI LE 12 km offaxs (-)	0.02	46	77	52	21	28	14	28	42
NuMI LE 12 km offaxs (+)	0.1	336	408	320	248	86	57	78	106
NuMI LE 12 km offaxs (-)	0.1	210	280	224	153	125	95	126	157
NuMI LE 40 km offaxs (+)	0.02	5.7	8.8	5.1	2.2	2.5	1.6	0.7	3.3
NuMI LE 40 km offaxs (-)	0.02	4.2	8.0	5.7	2.0	2.3	2.2	0.8	3.6
NuMI LE 40 km offaxs (+)	0.1	17	24	15	9.4	6.7	2.8	4.6	8.5
NuMI LE 40 km offaxs (-)	0.1	12	21	16	7.7	6.6	3.4	6.4	9.6
WBLE 1300 km (+)	0.02	141	192	128	77	19	11	18	36
WBLE 1300 km (-)	0.02	58	111	88	35	45	25	45	64
WBLE 1300 km (+)	0.1	607	720	579	467	106	67	83	122
WBLE 1300 km (-)	0.1	269	388	335	216	196	154	196	240
WBLE 2500 km (+)	0.02	61	103	88	46	11	4.6	4.7	11
WBLE 2500 km (-)	0.02	16	36	33	13	28	15	18	31
WBLE 2500 km (+)	0.1	270	361	328	238	27	13	13	28
WBLE 2500 km (-)	0.1	47	92	85	39	103	74	80	109

Charge current events per **100kT mass per 1 MW per 10^7 sec**

No detector model or backgrounds

(NuMI - 120 GeV
WBLE - 60 GeV)

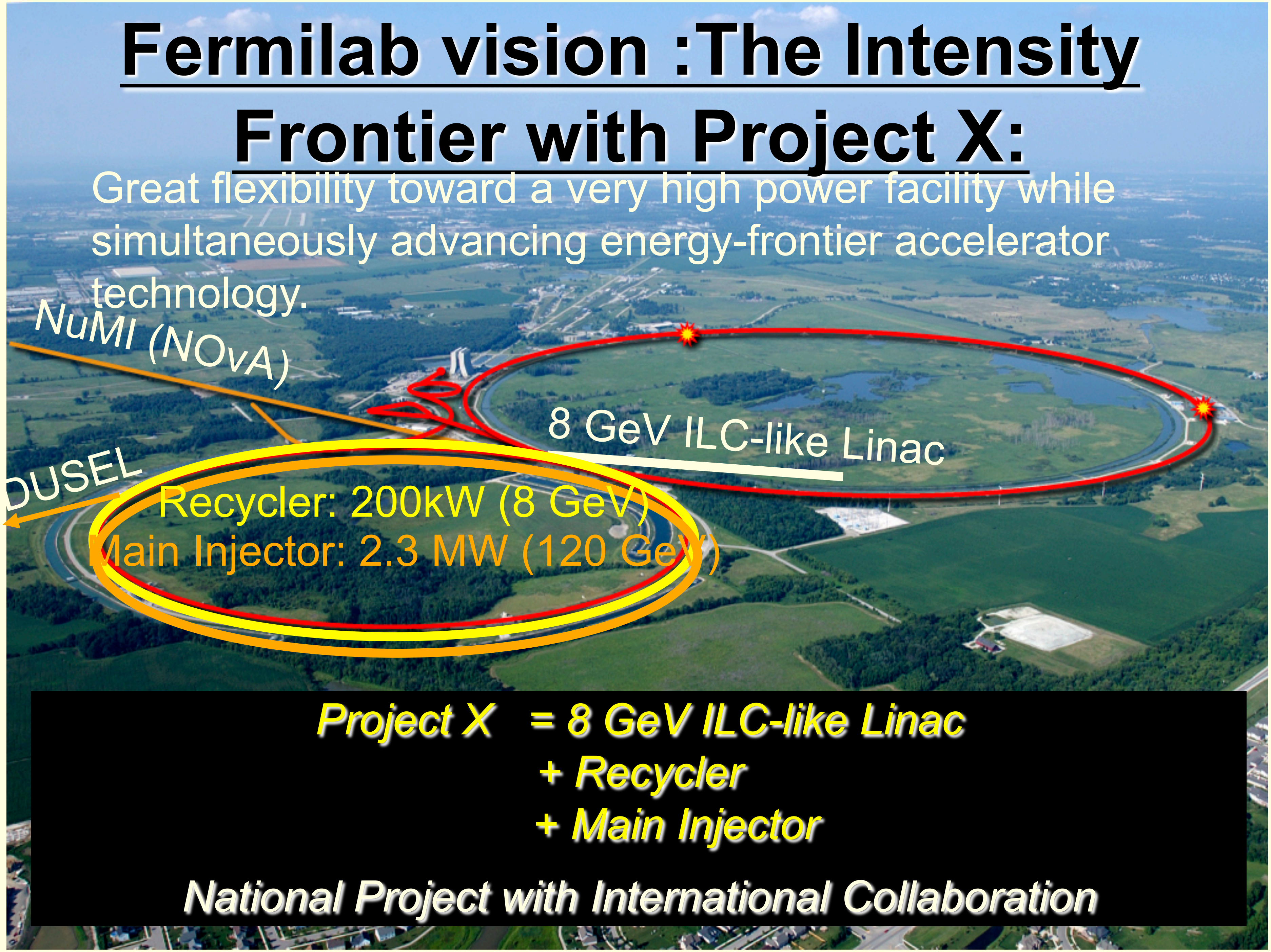
DUSEL rates

~10-1000 evts

From BNL/FNAL study (M. Bishai, B. Virin, M. Dierkerson)

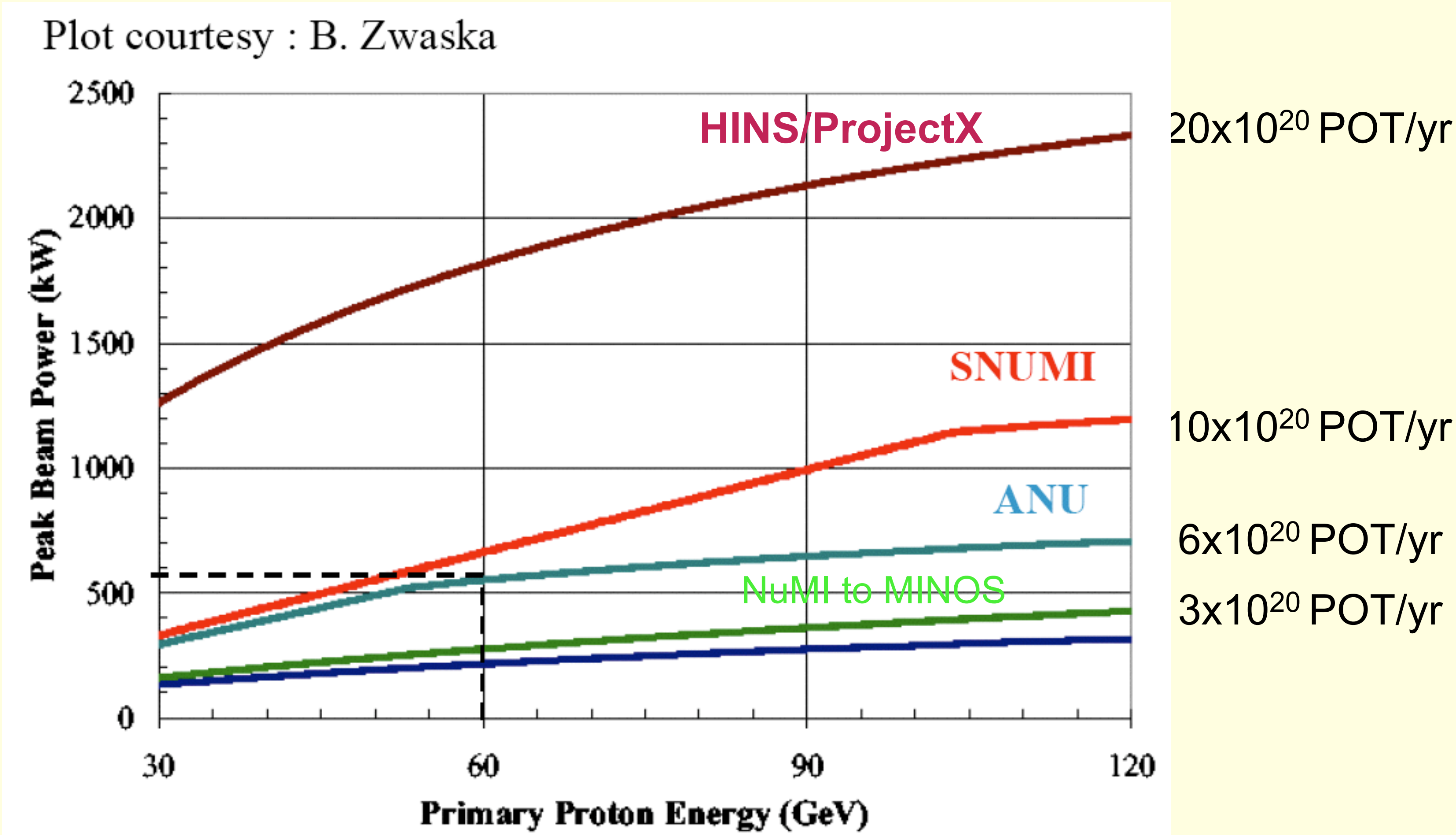
Fermilab vision :The Intensity Frontier with Project X:

Great flexibility toward a very high power facility while simultaneously advancing energy-frontier accelerator technology.



Project X = 8 GeV ILC-like Linac
+ Recycler
+ Main Injector

National Project with International Collaboration



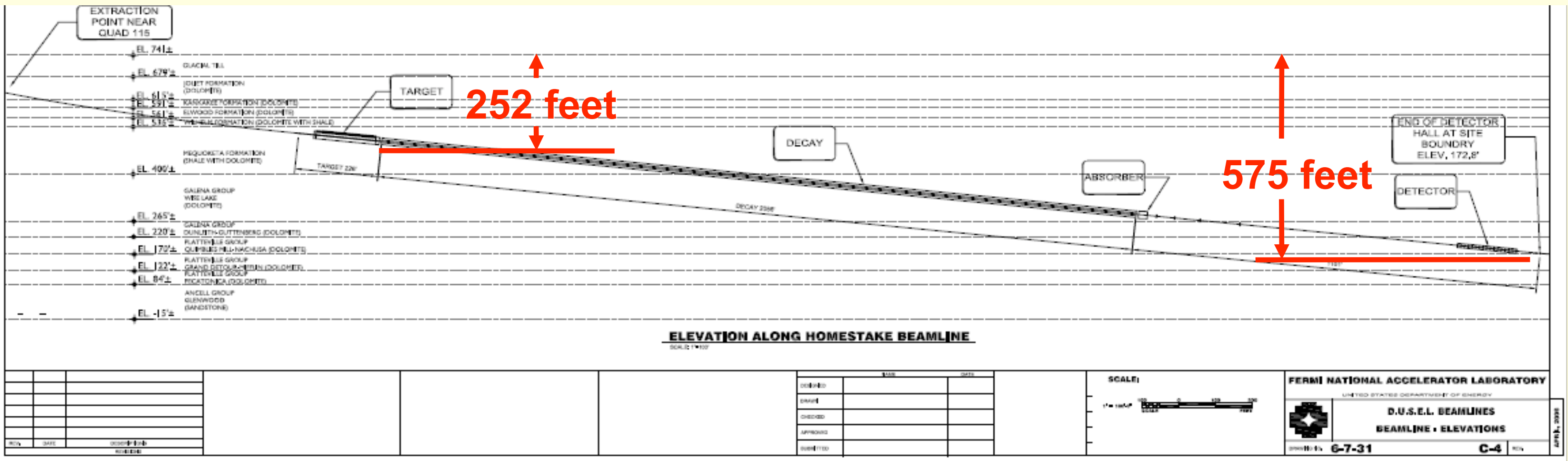
$$POT(10^{20}) = \frac{1000 \times BeamPower(MW) \times T(10^7 s)}{1.602 \times E_p(GeV)}$$

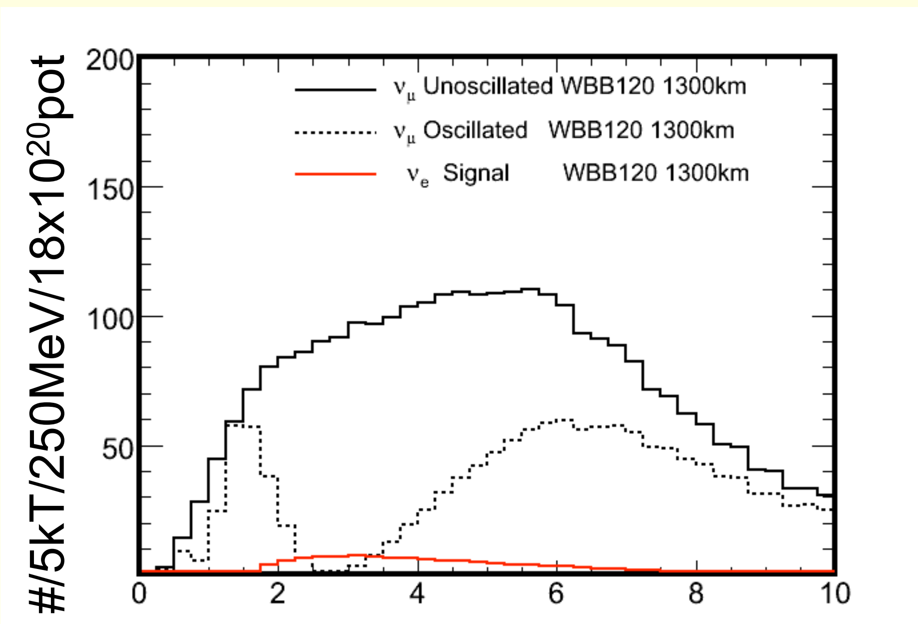
Neutrino Beam Requirements*

- The maximal possible neutrino fluxes to encompass at least the 1st and 2nd oscillation nodes, which occur at 2.4 and 0.8 GeV respectively
- Since neutrino cross-sections scale with energy, larger fluxes at lower energies are desirable to achieve the physics sensitivities using effects at the 2nd oscillation node
- To detect $\nu_\mu \rightarrow \nu_e$ at the far detector, it is critical to minimize the neutral-current contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is little sensitivity to the oscillation parameters is highly desirable
- The irreducible background to $\nu_\mu \rightarrow \nu_e$ appearance signal comes from beam generated ν_e events, therefore, a high purity ν_μ beam with as low as possible ν_e contamination is required

***From "Simulation of a Wide-Band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation Experiments", Bishai, Heim, Lewis, Marino, Viren, Yumiceva*

A beam to DUSEL : shorter & wider than NuMI



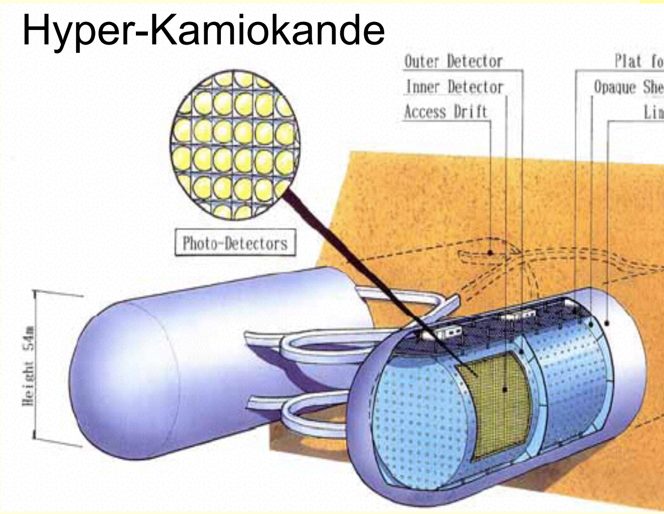


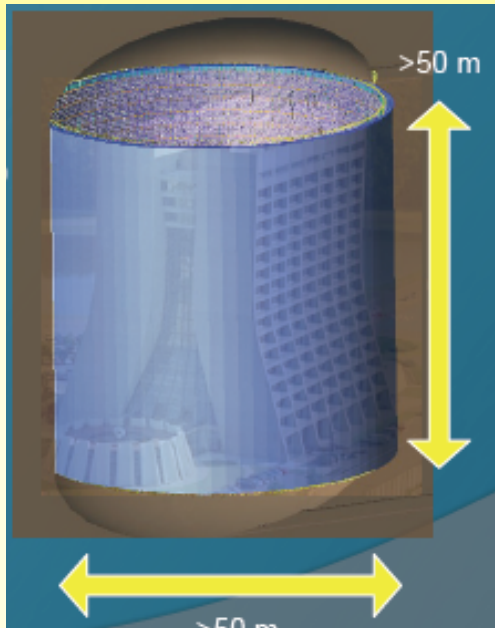
High power issues:
groundwater activation,
radioactive air emissions,
target stress,radiation damage,
decay pipe stress….

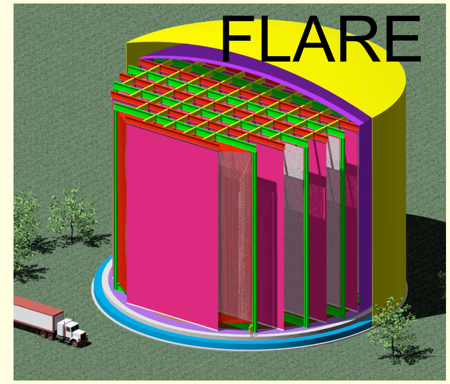
A super beam needs a super detector ….

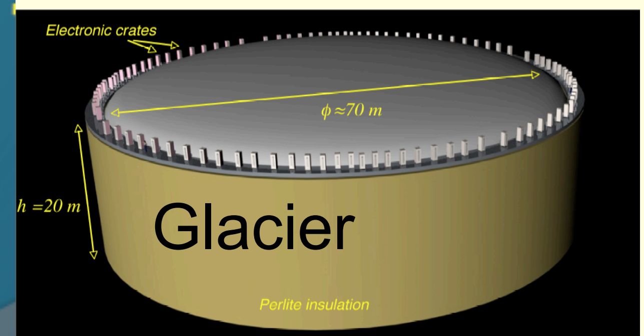
World Wide Concepts for Large Detector

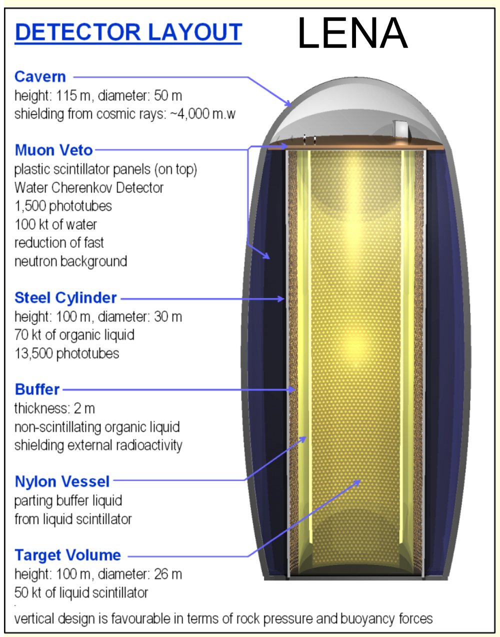
Water Cerenkov
Liquid Argon
Liquid Scintillator

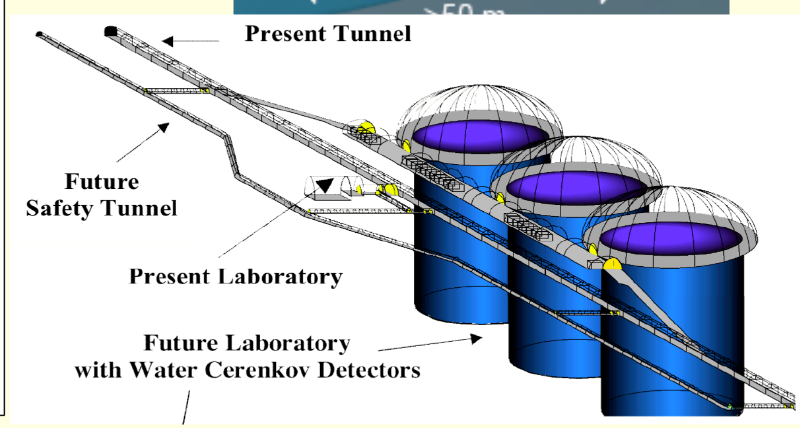


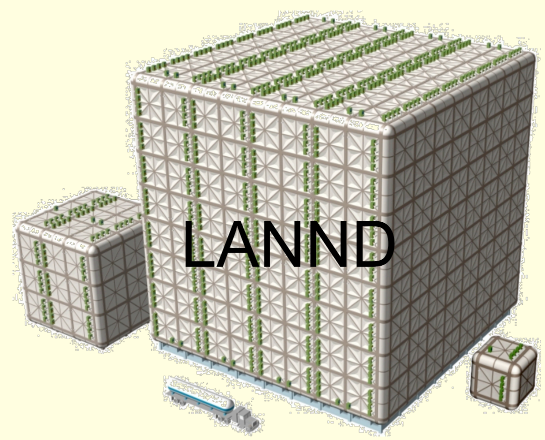




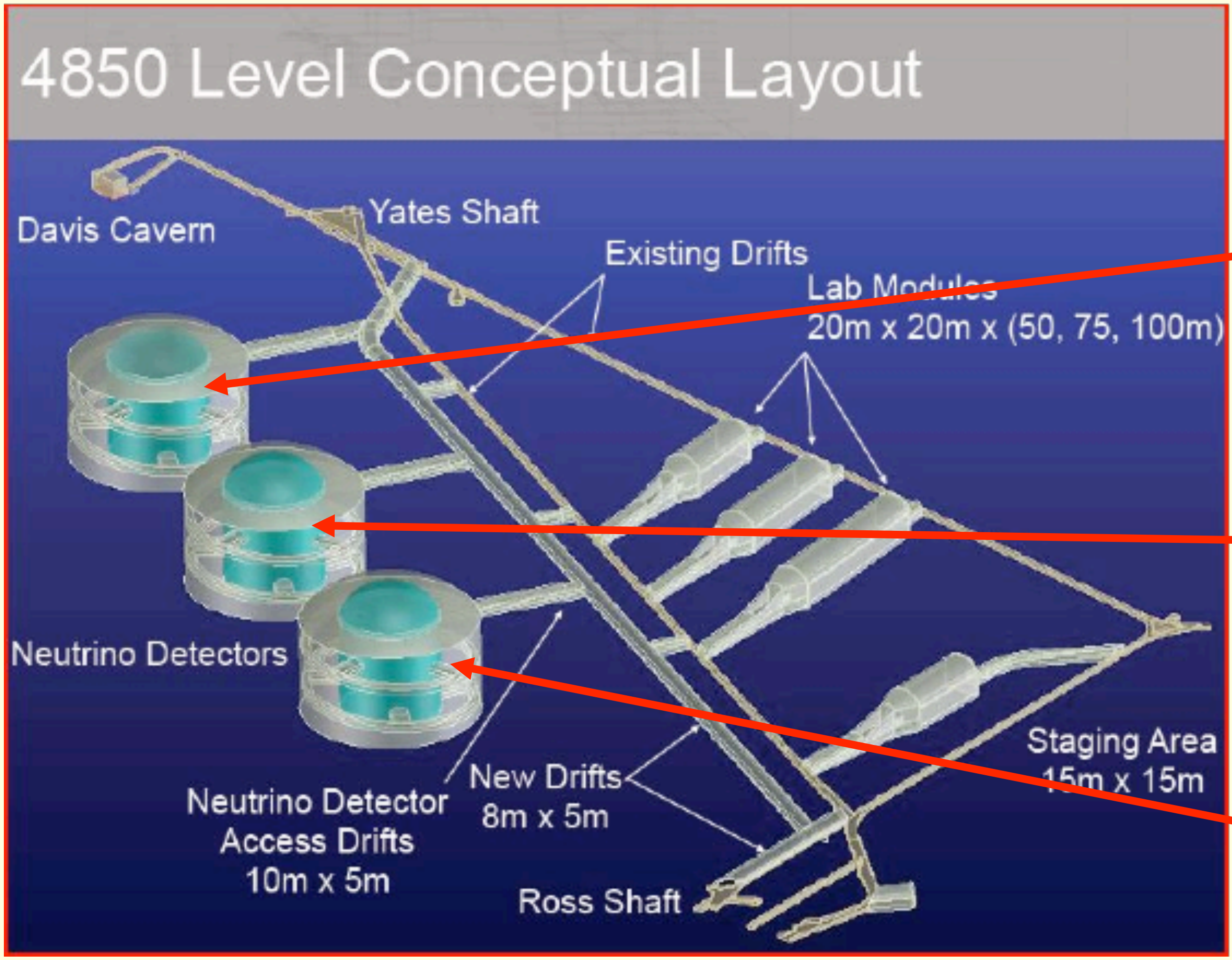


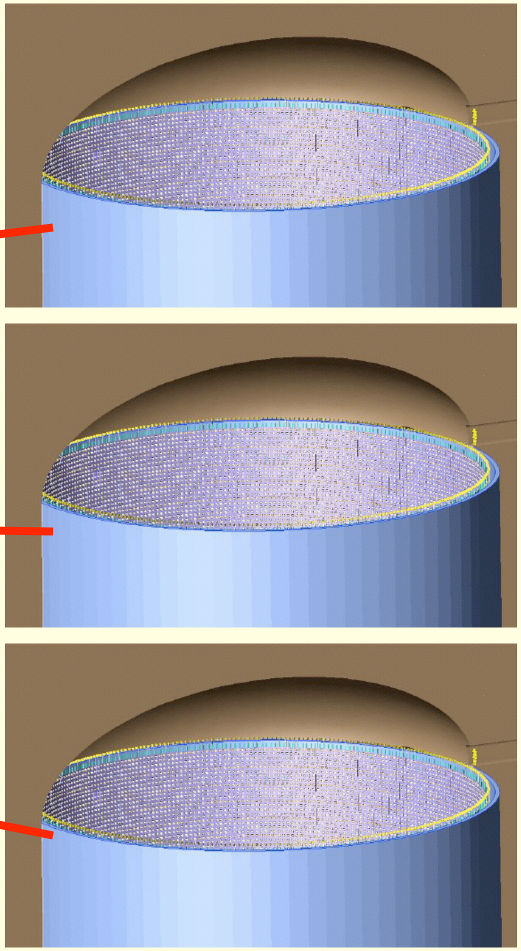






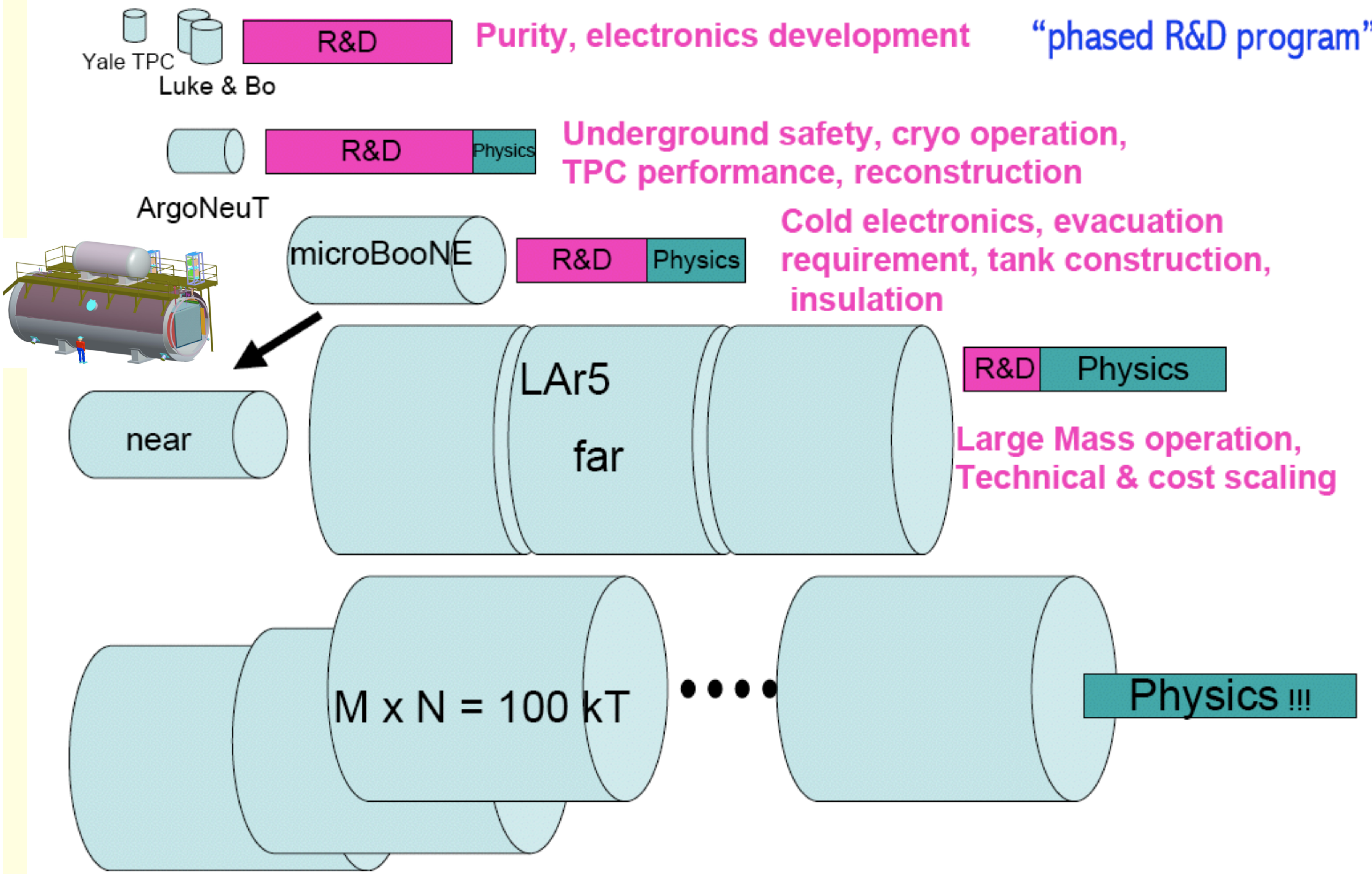
WC-100 x 3 @ Homestake DUSEL



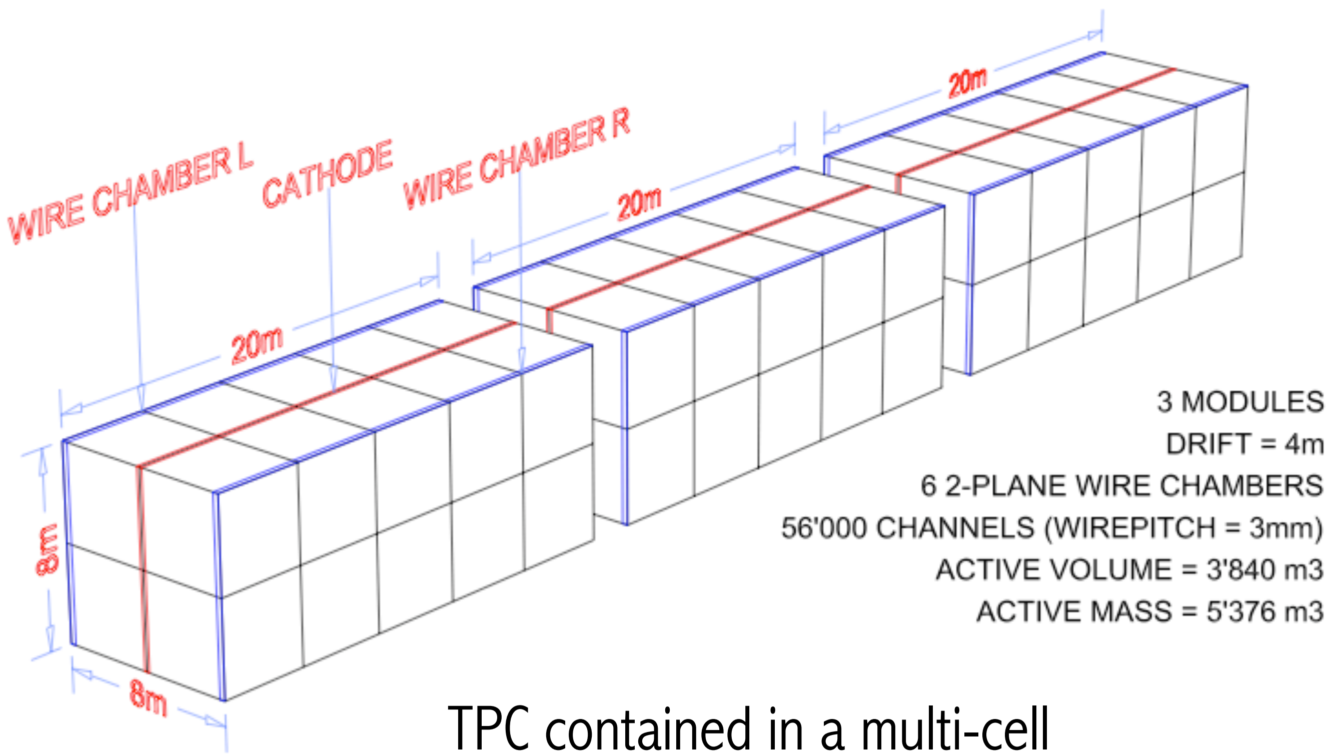


25% PMT coverage → 60,000 10 inch PMT's per module

Evolution of the Liquid Argon Physics Program



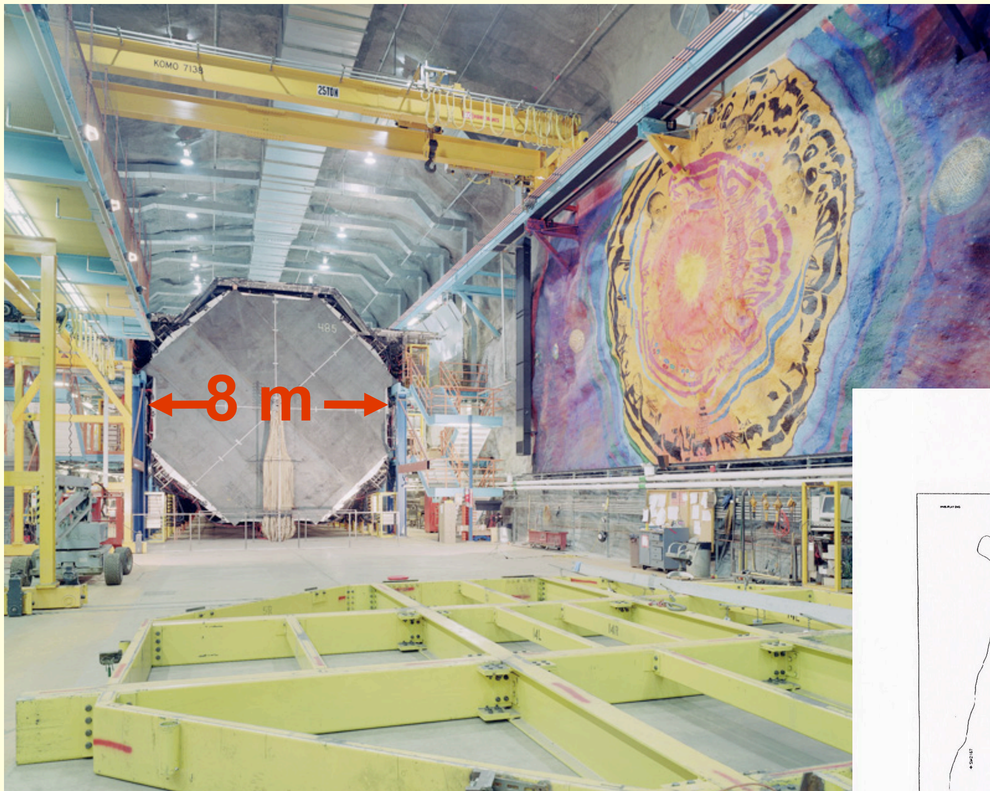
LANNDD Modular Concept

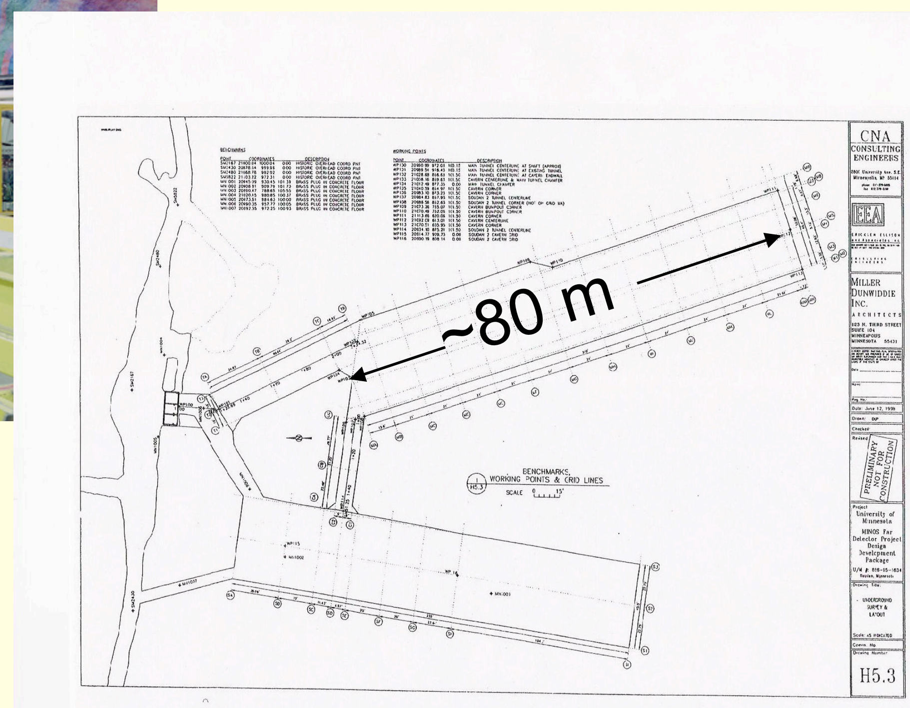


TPC contained in a multi-cell mechanical structure

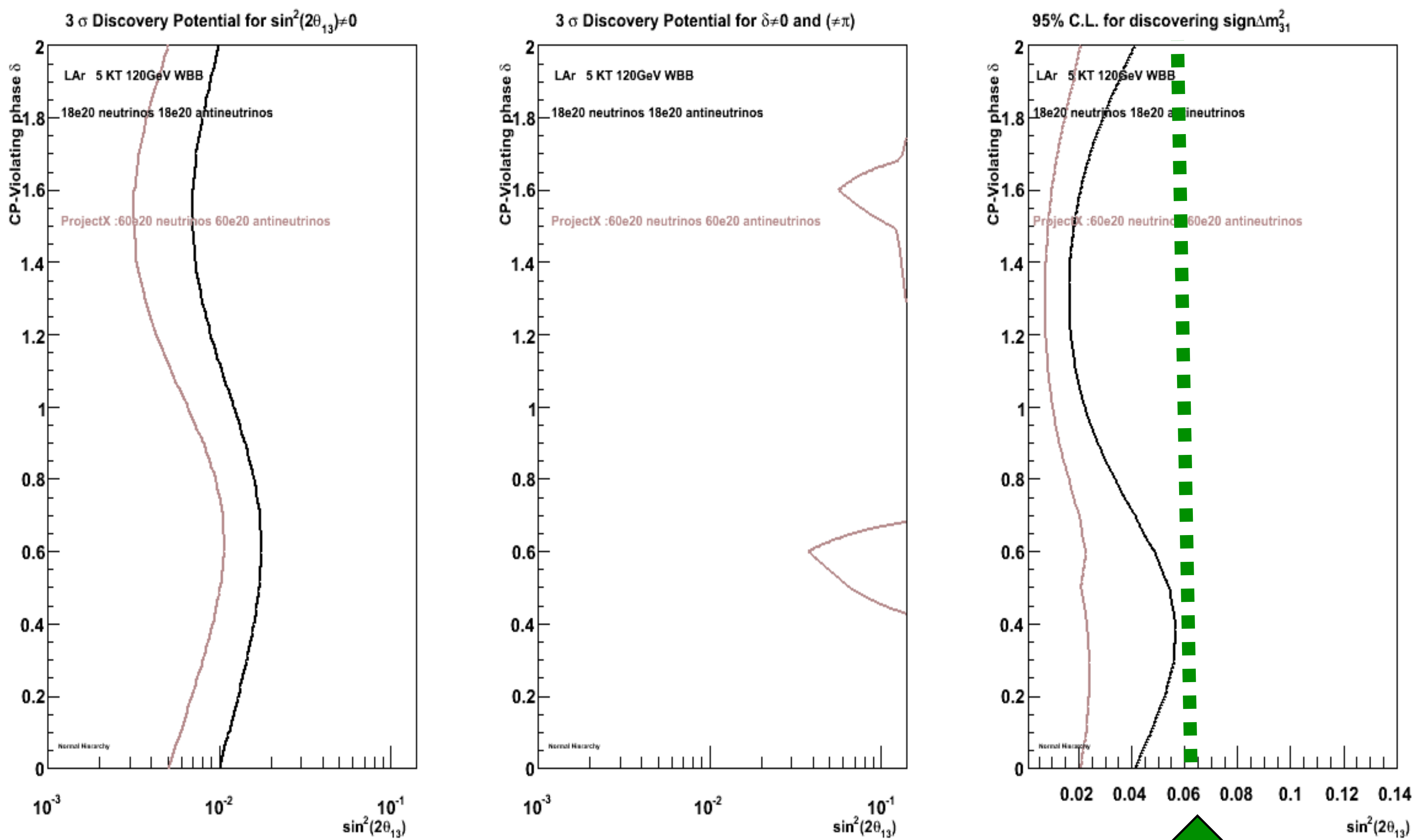
Drawing courtesy of D. Cline and F. Sergiampietri

The MINOS Cavern
at the Soudan Underground Laboratory





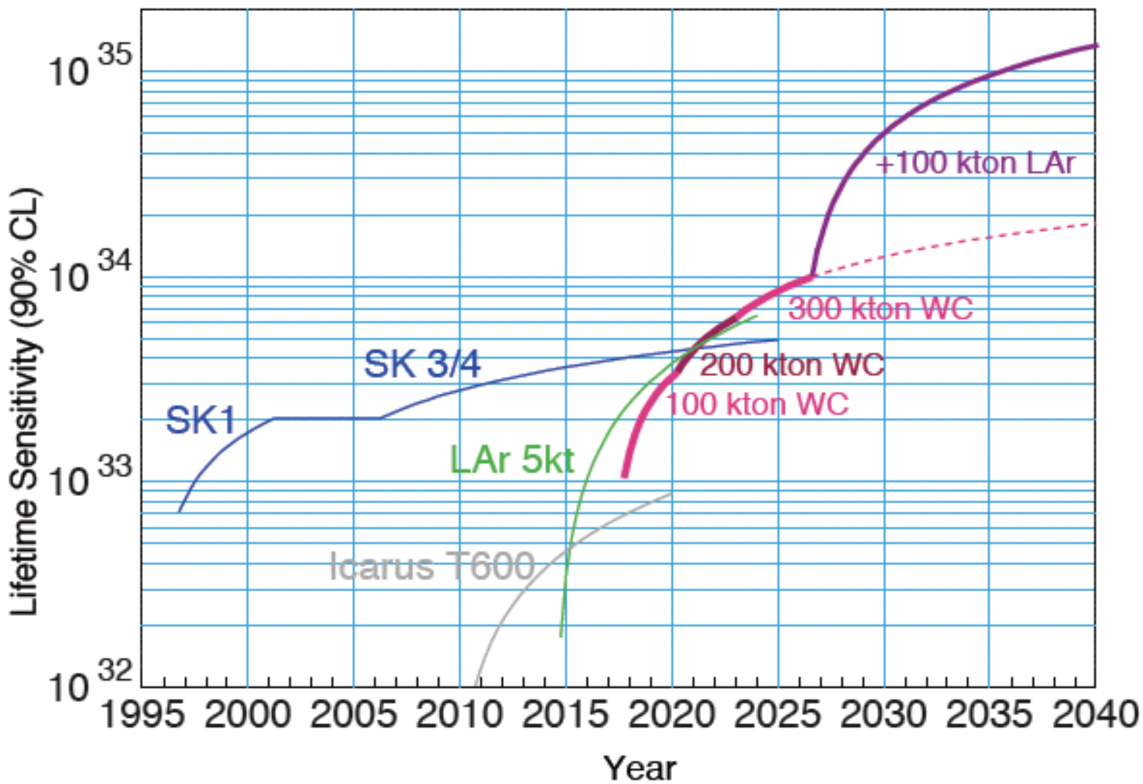
LAr5 at DUSEL



For $\sin^2 2\theta_{13} \sim 0.06$ sensitivity for all values of δ_{CP}

An added bonus, while waiting for the new neutrino beam…

$p \rightarrow K^+\nu$



WC efficiency = 0.14
BG = 1.2 evts/100 kty
Nobs = Nbg

LAr efficiency = 0.98
BG = 0.1 evts/100 kty
Nobs = Nbg

Key DUSEL Dates

•July 2007:	Homestake Site Selection for proposed DUSEL
•October 2008:	S4 solicitation for experimental proposals
•December 2010:	PDR-Preliminary Design Report, Baseline Scope, Schedule, Budget
•March 2011:	Earliest National Science Board Presentation of DUSEL MREFC proposal
•October 2012:	FDR Final Design Report for construction start in FY2013

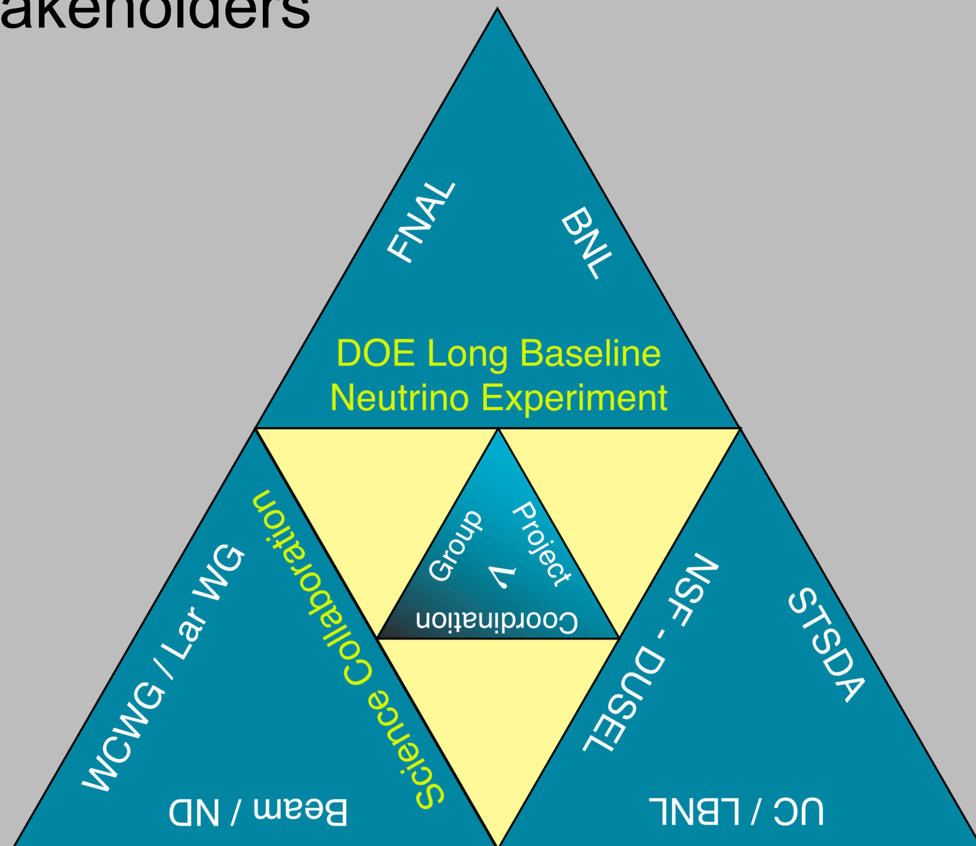
LB DUSEL “collaboration” Organization

- Several workshops/meetings since April
  - June 20, 2008 at FNAL
  - August 14, 2008 at FNAL
  - October 14-15, 2008 at BNL
  - February 26-28, 2009 at UC Davis
- Temporary Executive Committee formed
- Institutional Board of “interested groups” formed
- Collaboration by-laws being developed
- Detector technology groups submitted Proposals for the NSF S4 solicitation
- Collaboration Naming contest underway

Status of LBNE

- Fall 2008 – DOE prepared a Mission Need statement for a Long Baseline Neutrino Experiment (LBNE)
  - New neutrino beam to a Long Baseline
    - Can not be site specific at this time
  - Large Detector
    - Big enough to do CP violation and proton decay
- Spring 2009 – Expect Mission Need to be accepted and a CD-0 granted (Critical Decision Milestone : necessary to initiate a project)
- FNAL and BNL have been asked to make a plan to get to the next step (CD-1 : Conceptual Design) by the middle to end of 2010
- On this type of approval schedule one could imagine completing design and beginning construction ~2014-2015

Many “stakeholders”



Summary

- Over the past decade we have seen many exciting results from neutrino oscillation experiments looking at solar, atmospheric and accelerator neutrinos
  - We now know, to relatively good precision values for Δm^2_{12},Δm^2_{23},θ_{12} and θ_{23}

- Results from experiments to determine the third mixing angle, θ_{13}, are essential to laying out a strategy for further determination of the ν-mass-mixing matrix – in particular the parameter δ_{CP}, which will indicate whether or not CP is violated in the neutrino sector.

• If $\sin^2 2\theta_{13}$ ~≥ 0.05, with luck (and hard work) this result should be known by ~2012 from the Double Chooz, Daya Bay and T2K experiments

• In this case, the NOvA experiment (which could/should start taking data in ~2013-14) will be able to confirm and contribute information about the mass hierarchy and δ_{CP}

• Planning, leading to construction of a Phase II experiment, with a ν beam from Fermilab and massive detectors located at the DUSEL will offer the world wide neutrino community the opportunity to make precision measurements of neutrinos, as well as searches for proton decay and observation of astrophysical sources of neutrinos

• A broad range of experiments at the DUSEL will make it a flagship facility for the Science community

• If by 2013-14, the 1st round Phase I experiments have only measured limits on θ_{13}, these experiments need to continue towards discovery or their systematic limits; the NOvA experiment will come on line and quickly catch up; over the next several years these experiments will confirm or exclude that $0.01 \leq \sin^2 2\theta_{13} \leq 0.05$

• Confirmation should then accelerate the construction of the Phase II program

• Exclusion of $\sin^2 2\theta_{13}$ down to 0.01 indicates that further measurement of the parameters with a conventional neutrino beam will be extremely challenging

  • However, continued exploitation of the NuMI ν beam to a very massive detector (i.e. 10's of kT LAr at Ash River) could extend the limits on $\sin^2 2\theta_{13}$ down to ~ 0.005